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CONTROL FEASIBILITY STUDY FOR THE JOINT TECHNOLOGY DEMONSTRATOR--ETC(U)
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CONTROL FEASIBILITY STUDY FOR THE JOINT TECHNOLOGY DEMONSTRATOR ENGINE

Detroit Diesel Allison
Division of General Motors Corporation
Indianapolis, Indiana 46206 P.O. Box 894

October 1977

TECHNICAL REPORT AFAPL-TR-77-57

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report documents a program which demonstrated the feasibility of using a Bendix Model EH-K1 digital controller to operate the gas generator portion of a Joint Technology Demonstrator engine. The control modes were developed by Detroit Diesel Allison, Division of GMC, to achieve optimal specific fuel consumption and safe engine operation. A digital simulation of the control modes was interfaced with a digital simulation of the engine to determine schedules and compensation. The Energy Controls Division of Bendix

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Corporation, as subcontractor to Detroit Diesel Allison, then coded the control modes to be compatible with the EH-K1 instruction set. The software was tested on a ground-based version of the EH-K1 interfaced to a simplified, linear analog engine model. The testing demonstrated stable engine operation using the defined control modes.

FOREWORD

This technical report was prepared by Detroit Diesel Allison Division of General Motors Corporation with Bendix, Energy Controls Division as a major subcontractor. The effort was sponsored by the Air Force Aero-Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson AFB, Ohio, under Contract F33657-76-C-0021 for the period May 1976 to January 1977. The work herein was accomplished under Project 668A, Task 668A01, Work Unit 668A0110, with Marvin P. Wannemacher, AFAPL/TBP, as Project Engineer. Mr. Lester L. Small, AFAPL/TBC, technically directed the work. Mr. John A. Weber of Allison was technically responsible for the work. Other Allison personnel were D. E. Warner, K. A. Pieper, and R. C. Boyer. Bendix personnel were F. J. O'Keefe and R. C. Thomas.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont)

LIST OF TABLES

LIST OF SYMBOLS

A8	Variable Area Exhaust Nozzle
A/D	Analog to Digital Conversion
APSI	Advanced Propulsion Subsystem Integration
ATEGG	Advanced Technology Engine Gas Generator
BU X	Buildup No. X
CDP	Compressor Discharge Pressure
CJ	Cold Junction
CPU	Central Processing Unit
D/A	Digital to Analog Conversion
DAC	Digital to Analog Converter
DDA	Detroit Diesel Allison
DEMUX	Demultiplex
F_N	Net Thrust
HP	High Pressure
HPC	High-Pressure Compressor
HPC_1	High-Pressure Compressor Airflow Control Signal
HPC_2	High-Pressure Compressor Surge Avoidance Control Signal
HPT	High-Pressure Turbine
i. c.	Initial Condition
IGV	Inlet Guide Vane
IR&D	Independent Research and Development
JTD	Joint Technology Demonstrator
K	Gain
LVDT	Linear Variable Differential Transformer
N_H	High-Pressure Rotor Speed
N_{HC}	High-Pressure Rotor Speed (corrected to rotor inlet)
P	Total Pressure
PLA	Power Lever Angle

LIST OF SYMBOLS (Cont)

P_{XS}	Static Pressure at Station Location X
P_{XT}	Total Pressure at Station Location X
P + I	Proportional plus Integral
R	Pressure Ratio
REF	Reference
REQ	Request
RIT	Rotor Inlet Temperature
RPR	Ram Pressure Ratio
S	Laplace Variable
SFC	Specific Fuel Consumption
S/H	Sample and Hold
T	Temperature
T/C	Thermocouple
T_X	Temperature at Station Location X
TBT	Turbine Blade Temperature
TIT	Turbine Inlet Temperature
VG	Variable Geometry
W_a	Airflow
W_f	Fuel Flow
W_{fA}	Channel A Fuel Flow
W_{fB}	Channel B Fuel Flow
Δ	Differential
δ	Correction Factor for Standard Pressure
ϵ	Error
θ	Correction Factor for Standard Temperature
τ	Time Constant

SECTION I

INTRODUCTION

The Detroit Diesel Allison (DDA) Joint Technology Demonstrator (JTD) program requires engine controls of varying levels of sophistication to perform contracted and other anticipated engine tests. The transient testing involved requires an active controller with multi-loop capability. The purpose of the JTD Control Feasibility Study (Contract No. F33657-76-C-0021) was to determine the feasibility of using the Bendix Model EH-K1 digital controller to operate the JTD gas generator (GMA200 ATEGG) and subsequently the JTD itself. The EH-K1 controller is designed to be engine mounted on a typical Mach 2.5 aircraft engine and incorporates a Bendix 920 microprogrammed, 16-bit processor with custom-designed input/output.

The first major task of this program was defining the control system. In this task DDA developed the control modes for the JTD gas generator testing. These control modes were then modeled on the DDA digital computer in conjunction with the digital model of the JTD gas generator to establish control mode constants and failure modes. DDA prepared (1) a software specification containing functional and checkout requirements and (2) a hardware specification containing interface and environmental requirements.

The second major task was establishing the feasibility of adapting the EH-K1 to meet these specifications. As a part of this task, DDA reviewed the results of breadboard tests conducted under a separate Bendix development program to evaluate input/output circuitry adapted for controlling ATEGG. A second part of this task was the development by Bendix of software corresponding to the control modes defined under Task I. This software was compatible with the BDX 920 Central Processing Unit. Another part of this second major task was DDA preparation and checkout of a simplified linear analog model of ATEGG. As the final part of this task, Bendix checked out the computer software with the simplified linear analog model. The software was implemented on the BDX 9000 computer, a ground-based version of the aerospace designed BDX 920 CPU with identical instruction sets. Transient, steady-state, and self-check performance were to be evaluated.

SECTION II

SUMMARY

The control mode for the JTD gas generator (ATEGG) testing has been developed. It has been designed to handle the test cell conditions anticipated including artificially elevated inlet temperature and pressure as well as ambient conditions. The original basis for controlling the engine was to achieve optimal SFC. This goal was later amended to ensure safe engine operation.

The control mode concerns itself with the following tasks: (1) fuel metering, (2) compressor variable vane modulation, (3) turbine variable vane modulation, (4) variable area exhaust nozzle modulation, and (5) failure detection. Fuel modulation is handled by a closed-loop speed governor with scheduled acceleration and deceleration. The ability also exists to limit fuel to prevent engine parameter limits from being exceeded. Compressor variable vane modulation is a scheduled function of corrected speed to provide surge-free operation. The turbine variable vanes are modulated to control turbine outlet temperature on a closed loop basis. The variable area of the exhaust nozzle is modulated to maintain desired engine operation for a given power level. Reasonableness checks are performed on critical engine signals to indicate engine failure.

A digital simulation of the control mode selected was interfaced with a nonlinear dynamic digital simulation of the JTD gas generator. Schedules and preliminary compensation used in the control were established through transient operation of this engine simulation.

The computer software was developed to ultimately accommodate the entire JTD control mode. The ATEGG logic was programmed within this software for further testing of the selected control mode. This testing consisted of exercising the controller on real time linear and nonlinear engine models. The real time models were based on linear model data extracted from the ATEGG simulation and simulated on analog computers. Extensive testing against these models was very successful and led to the achievement of compensation necessary for stable engine operation.

The hardware and software specifications have been prepared to detail necessary system requirements.

SECTION III

ADVANCED TURBINE ENGINE GAS GENERATOR (ATEGG) ENGINE DESCRIPTION

The GMA200 gas generator (Figure 1) is a highly sophisticated and flexible test unit featuring advanced technology components. The primary objective of the technology development is to demonstrate the performance, structural, and operating characteristics leading to an engine that is significantly advanced in terms of stage loading, material application, and component variability.

A brief description of each of the ATEGG components technology is presented in the following sections.

1. COMPRESSOR

The GMA200 HP compressor is a six-stage unit with variable flow capacity. All stationary vane rows except the outlet guide vanes have the capability for variable setting angle. The compressor rotor construction incorporates advanced titanium materials and design features

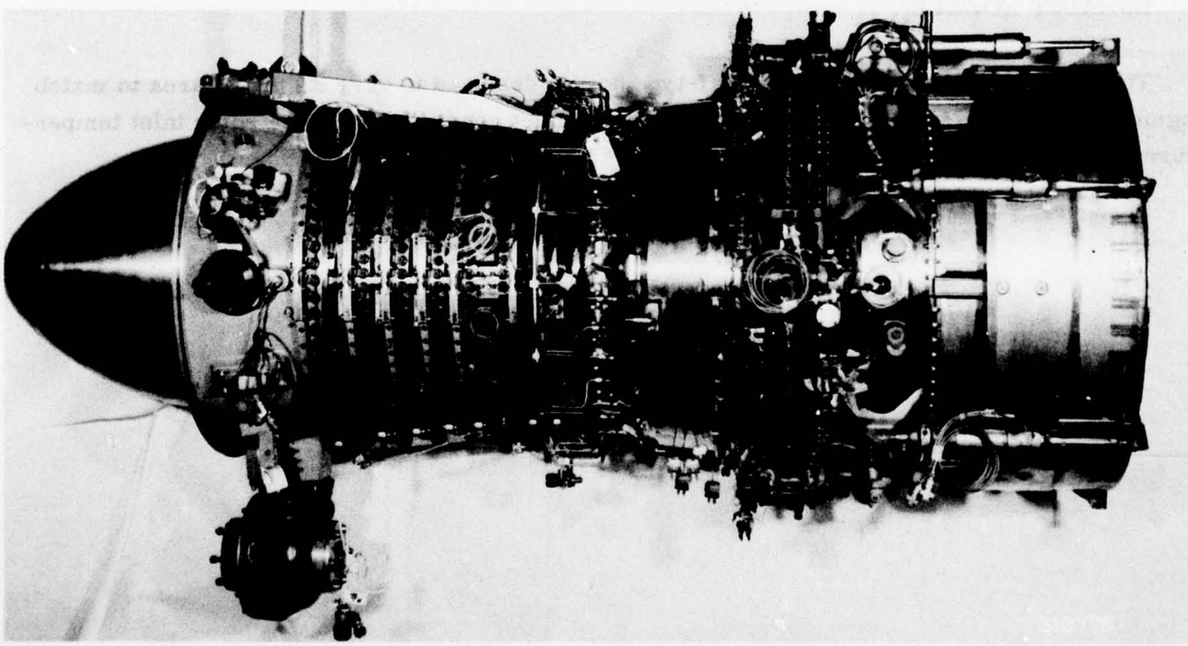

Figure 1. GMA200 Gas Generator.

resulting in a single, lightweight structure using optimum materials selected to match the design requirements imposed by the varying temperature and stress conditions through the compressor. Other attractive features of this type of compressor design include:

- Maximum variability in airflow capacity and flow-speed relationship suitable for supersonic flight
- Surge relief at low compressor speeds

2. COMBUSTOR/DIFFUSER

The GMA200 combustor uses staged combustion technology for high temperature combustion. The diffuser/combustor system is a triple-passage diffusion system which includes a communicating channel and boundary layer bleed and convection/film cooling. The use of two combustion reaction zones provides for efficient and stable operation over a very broad range of outlet temperatures.

3. TURBINE

The GMA200 gas generator features a variable capacity turbine with mechanically variable nozzle guide vanes and transpiration-cooled airfoils. It is a high-work, variable-flow-capacity, maximum-temperature, single-stage assembly.

4. EXHAUST NOZZLE

The GMA200 exhaust nozzle is a leaf-type nozzle designed to vary its throat area to match engine requirements under various combinations of inlet conditions, turbine rotor inlet temperatures, HP turbine areas, and rotor speeds.

SECTION IV

DIGITAL COMPUTER DYNAMIC SIMULATION

A highly sophisticated digital computerized dynamic engine and controls simulation was developed to support the controls design and evaluation required by this project. The simulation is a derivation of the full JTD simulation referenced in AFAPL-TR-76-49. Figure 2 shows the gas path for the ATEGG simulation with corresponding station numbers and controllable engine inputs. These station numbers are used as subscripts on engine parameters to denote the location of the temperature, pressures, flows, etc, through this report. Station 2.1 actually represents engine inlet for the gas generator and thus, for this study, is interchangeably referred to as Station 1. The ATEGG simulation allows steady-state design and off-design operating points to be examined. The model may also be run in a transient mode with full variable geometry capability.

1. STEADY STATE

DDA computerized, steady-state performance programs are designed on a building block concept and consist of a controlling logic routine which links a system of generalized component subroutines into any desired type of engine configuration defined by inputs. The ATEGG general program structure is represented in Figure 3.

The program option selection box indicates that several options exist for changing the variable geometry to satisfy certain criteria. Two options exist for the steady-state case.

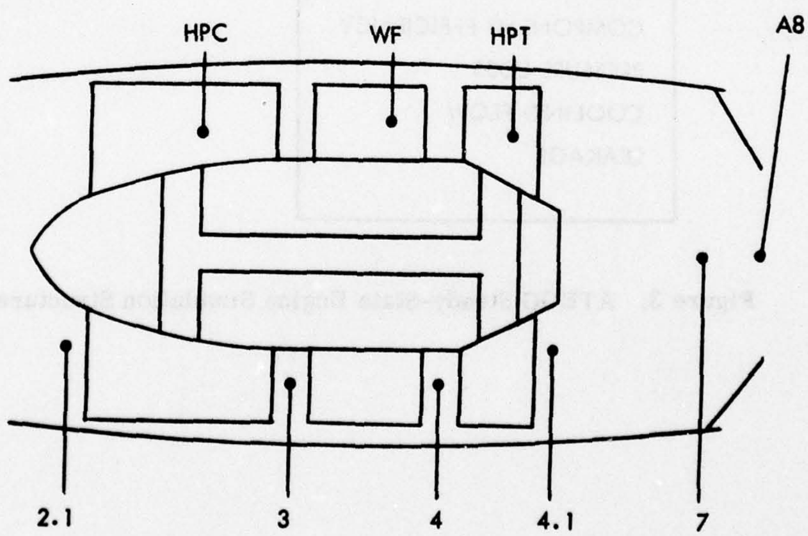

Figure 2. ATEGG Schematic.

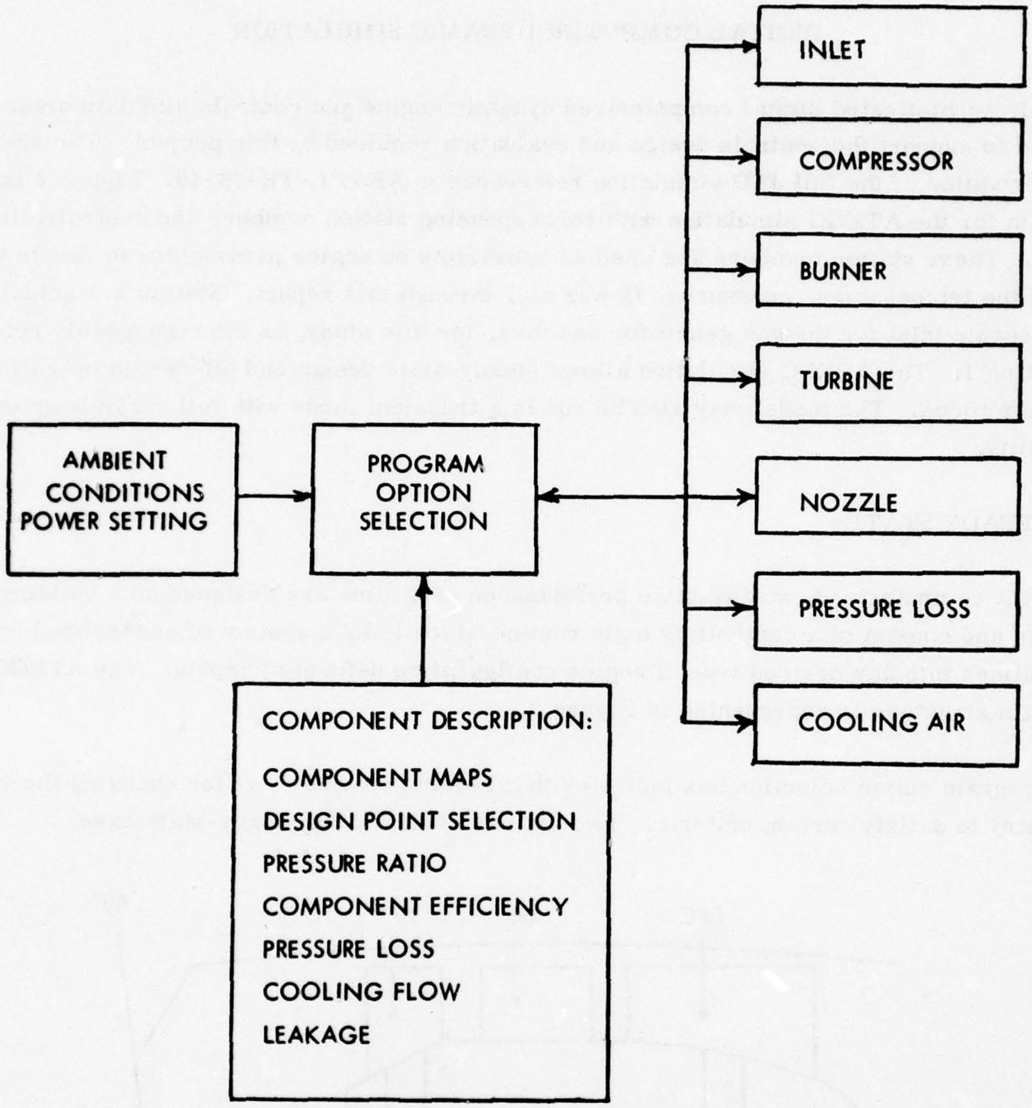

Figure 3. ATEGG Steady-State Engine Simulation Structure.

a. Constraint System

The first steady-state option is a constraint system in which the geometry settings to be varied are specified. The constraint system forces these geometry settings to positions which satisfy an equal number of compatible constraints. The system generates a set of simultaneous linear differential equations to relate the selected variables with their effect on matching the selected constraints. Through an iteration process, these equations reposition the geometry settings to satisfy those constraints. The constraints available on ATEGG are:

- Compressor Rotor Speed
- Corrected Compressor Rotor Speed
- Engine Net Thrust
- Compressor Surge Margin
- Turbine Rotor Inlet Temperature
- Primary Nozzle Temperature
- Compressor Discharge Pressure
- Engine Inlet Airflow
- Engine Corrected Inlet Airflow
- Engine Fuel Flow
- Primary Nozzle Area
- Compressor Variable Geometry Setting
- Turbine Variable Geometry Setting

b. Optimization System

The optimization system is designed to maximize net thrust or minimize specific fuel consumption by automatic manipulation of one or more variable-geometry components simultaneously. All defined engine limiters can be maintained for engine matching, and maximum and minimum setting limitations can be imposed on each variable-geometry component.

The method used involves the search for zero slope on a generated curve of net thrust or specific fuel consumption versus each variable geometry component position. The iteration procedure varies all the geometry settings individually on each pass to generate the curves, then produces new settings for the components simultaneously for the next iterative pass based on zero slope estimates derived from those curves. The iteration process is satisfied when each variable-geometry component setting meets any one of these criteria: (1) its slope versus F_N or SFC is within a tolerance of zero; (2) it has reached its maximum or minimum limited setting; (3) its variation plus and minus did not significantly affect the parameter being optimized (F_N or SFC).

2. TRANSIENT

Transient analysis of the system is accomplished by additional dynamic routines being interfaced with the steady-state simulation. These additional routines perform the control of time functions, rotor dynamics, and heat storage effects to produce engine response time history characteristics. Transient operation of the simulation permits two more options for changing variable geometry. These are time history modulation and modulation through control. This augments Figure 3, as indicated in Figure 4.

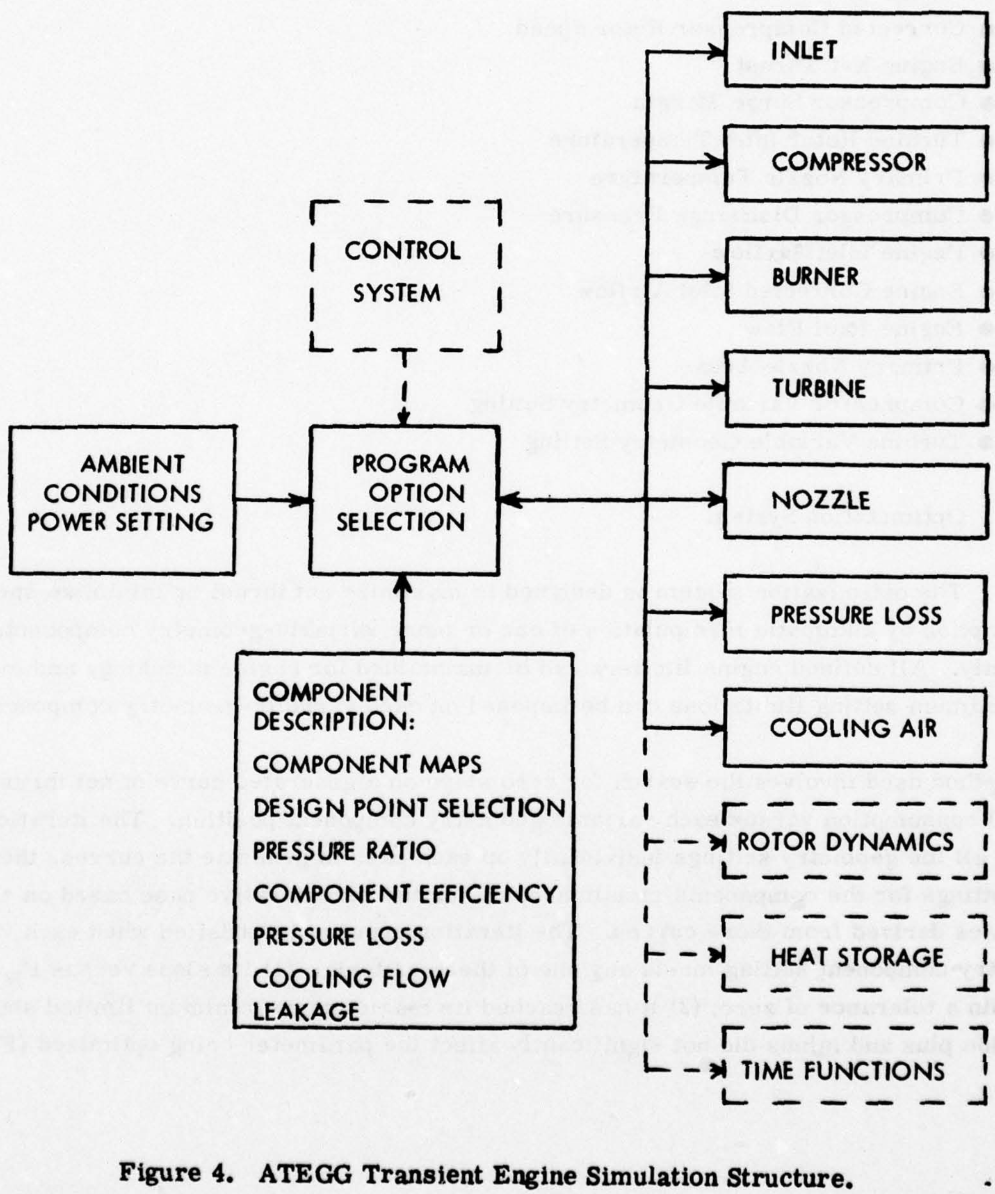

Figure 4. ATEGG Transient Engine Simulation Structure.

a. Time History

The ability exists to alter each piece of geometry on a time history basis. This ability also exists for a variation versus time of fuel flow. This option has the advantage of permitting examination of engine dynamics over the entire engine operating region.

b. Control

The control system included in the dynamic computer simulation is capable of evaluating various control modes (laws) for controlling the engine. The control system simulation can also be used to evaluate requirements for sensor response and accuracy, actuator characteristics, control loop capability, system stability, failure modes, and control loop solution rates. The control of the HPC geometry position for maximum surge margin and efficiency is built into the open, nominal, and closed compressor maps used in the engine simulation.

Figure 5 shows the control system as it interfaces with the engine simulation. As can be seen, the inputs to the sensor dynamics are really the outputs from the engine simulation consisting of engine parameters and geometry positions. The control laws for each variable component represent calculations done inside the controller. As indicated, the control system simulation is broken into subsystems (computer subroutines) with the ability to interface with each other. The actuator models and fuel metering system model are an attempt to represent the corresponding engine hardware components.

(1) Sensor Models

The sensors being used on ATEGG are detailed in the hardware specification (Appendix A). For simplicity, all pressure transducers were simulated as a single lag although many transducers actually are better characterized by an overdamped second order lag. This simplification is justified by the fact that the lags introduced by pressure transducers are usually not within the bandwidth of the control loop in question. Thus, the input-output relationship of the pressure transducers is given by

$$\text{Sensed Pressure} = \frac{1}{1 + 0.02S} \text{Actual Pressure}$$

The lags introduced by speed sensors are even more negligible than pressure transducers so that a simple first order lag is adequate. Thus, the speed sensor is represented by

$$\text{Sensed Speed} = \frac{1}{1 + 0.01S} \text{Actual Speed}$$

for both spool speeds. For any accuracy analysis, the actual mechanization scheme must be considered along with the expected "quantization noise" generated with a digital signal.

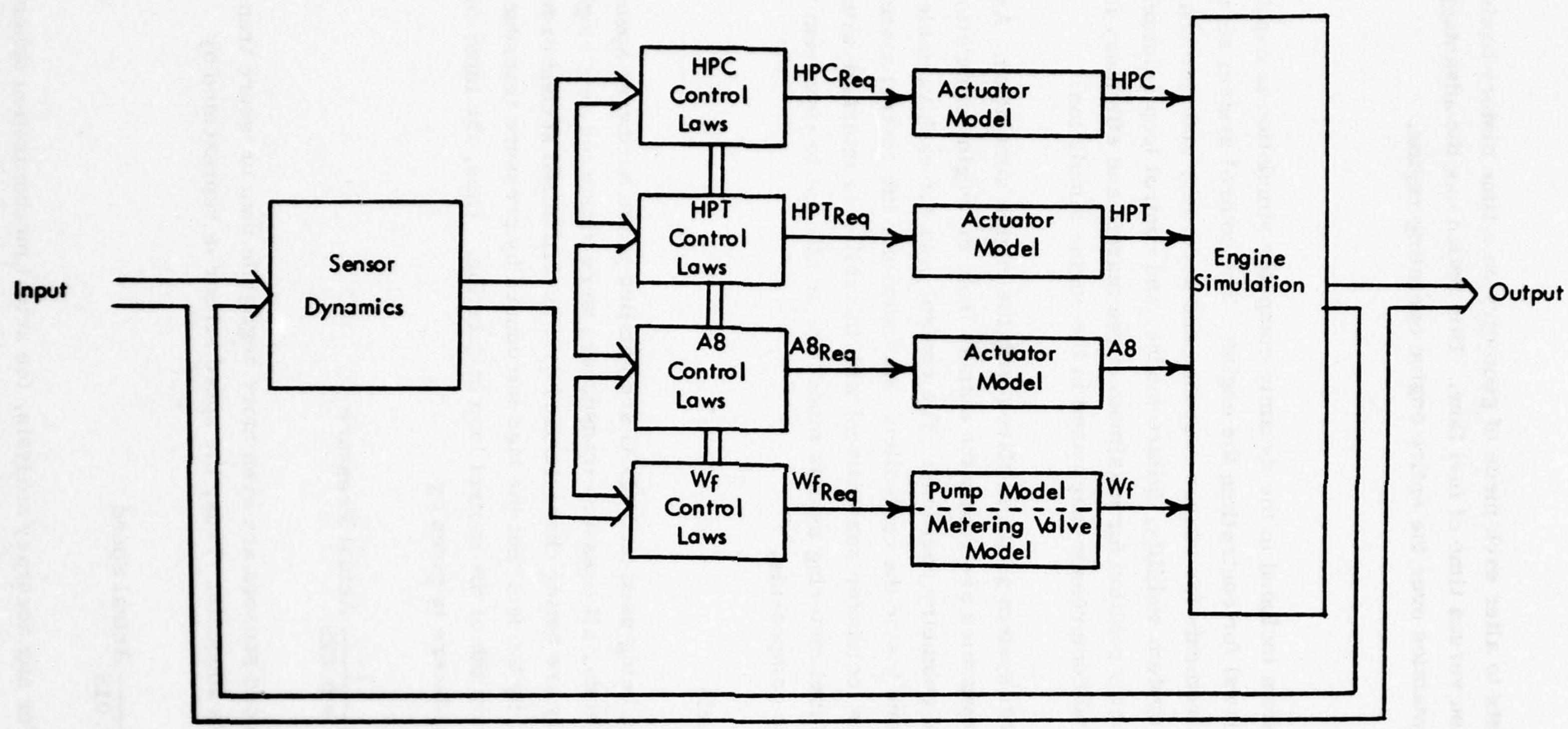

Figure 5. ATEGG Control Simulation Structure.

The temperature sensors are also represented by a first order lag which is adequate for the type of sensors (thermocouples) used in ATEGG. However, the time constant of the thermocouple is usually a function of the airflow in the gas path being measured. The input-output relationship used for the temperature sensors is

$$\text{Sensed Temperature} = \frac{1}{1 + \tau_{Temp} S} \text{Actual Temperature}$$

where

$$\tau_{Temp} = \tau_{sensor} \sqrt{\left(W_{standard} / W_{actual}\right)}$$

and

τ_{sensor} = sensor time constant at an airflow of $W_{standard}$

W_{actual} = actual airflow

An important factor in parameter sensing impractical to simulate is the errors created by pressure and temperature "distribution" and the sensor location. Engineering judgement must be exercised in this area when assessing the "error" contribution of the sensors.

(2) Actuator Models

The actuators on the variable turbine and variable nozzle are specified in the Hardware Specification (Appendix A). The simulated models for both took the form shown in Figure 6. A rate command from the control is multiplied by a gain to produce a rate motion of the actuator. This rate is limited in the actuator and integrated to produce the actuator position. The actuator position also experiences hysteresis and position limiting.

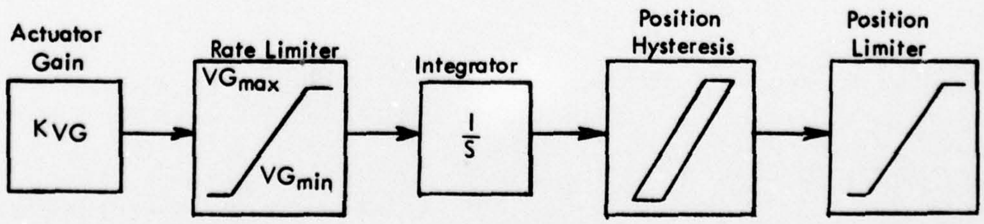

Figure 6. Simplified Actuator Model Used in Simulation.

(3) Fuel System Model

The fuel system to be modeled for the ATEGG nonlinear simulation consists of two electrically driven TF41 variable displacement pumps and two Pegasus fuel valves. The model representing this system consists of two first order lags. This type of model is justified by experimental data on a TF41 pump and metering systems.

SECTION V

ATEGG CONTROL MODE STUDY

The ATEGG control mode logic is implemented in a Bendix EH-K1 computer. Appendix B is the software specification for this minicomputer. The EH-K1 is the unit designed for use on the JTD. Since the gas generator represents the core of the JTD, the preliminary design specification for the control logic was to make it as similar to the core JTD logic as possible (described in AFAPL-TR-76-49).

The gas generator is a test cell engine. As such, the gas generator control logic has been tested for not only ambient conditions but also conditions of elevated inlet pressure and/or temperature to simulate JTD fan exit conditions. Presently maximum expected inlet conditions are:

P_{max} Inlet = 42.6 psia
T_{max} Inlet = 275°F

The first step used in determining the control logic was to choose an engine operating line. The digital simulation was used extensively in determining the operating line. As an initial pass, minimum SFC for all inlet conditions was sought. The optimization option of the simulation, as previously discussed, was used to accomplish this. Updated test information on compressor characteristics necessitated sacrificing SFC in some areas to ensure safe engine operation. The constraint option of the simulation, as previously discussed, was used for this. The geometry position and fuel flow necessary to achieve minimum SFC were utilized as a base for this part of the study. The final result of this effort was the fuel flow and the positioning of each piece of geometry necessary to yield safe engine operation as a function of engine inlet conditions. Given the effect of these fuel flow and geometry settings on engine parameters, the control logic was formulated and evaluated under the transient control option of the simulation. The remainder of this section discusses the final logic formulation for the ATEGG digital controller including signal processing, fuel modulation logic, geometry modulation logic, and signal synthesis efforts.

1. SIGNAL PROCESSING

The signal processing section of the control mode performs reasonableness tests on all engine signals used by the control logic as well as providing any signal compensation necessary. A typical loop testing for signal reasonableness is shown in Figure 7. The engine signal is passed through a multiplexing A/D converter and adjusted for A/D offset. The resulting signal is checked versus maximum rate changes normally expected. If the rate exceeds this maximum rate check, a failure trigger is set. Similar processing exists for making sure the signal is within reasonable operating limits. The signals requiring compensation have lead or lag networks after the range check. The resulting signals are processed to the control logic. Other

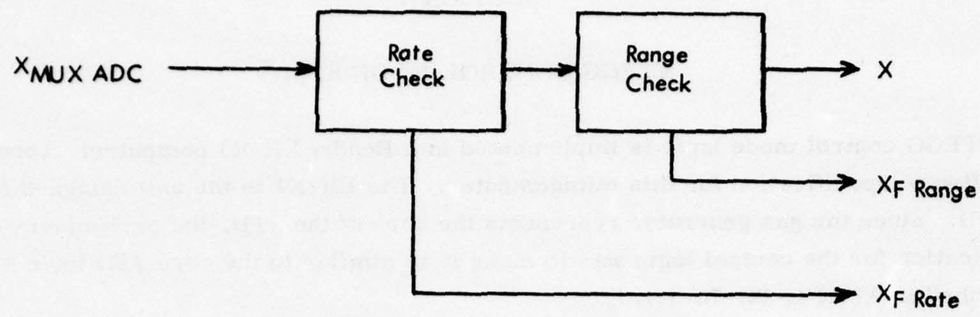

Figure 7. Signal Reasonableness Logic.

functions accomplished in the signal processing section are the ability for cold junction compensation of temperature signals, the formulation of other signals needed by the control logic, and the selection of the signal to be processed in the case of two or more engine feedback signals.

The following is a list of the engine signals being processed for use in the ATEGG control logic and the corresponding unit:

- PLA Power Lever Angle (degrees)
- N_H Compressor Rotor Speed (rpm)
- T_1 Engine Inlet Temperature (°R)
- T_3 Compressor Discharge Temperature (°R)
- TBT Turbine Blade Temperature (°R)
- $T_{4.1}$ Turbine Outlet Temperature (°R)
- P_1 Engine Inlet Pressure (psia)
- P_{3T} Compressor Discharge Total Pressure (psia)
- P_{3S} Compressor Discharge Static Pressure (psia)
- $P_{4.1}$ Turbine Outlet Pressure (psia)
- P_7 Exhaust Nozzle Pressure (psia)
- HPC_1 Position of Compressor Geometry for Flow Control (%)
- HPC_2 Position of Compressor Geometry for Surge Control
- HPT Position of Turbine Geometry (degrees)
- A8 Exhaust Nozzle Area (in.^{2})
- W_{fA} Primary Channel Fuel Flow (lb/hr)
- W_{fB} Secondary Channel Fuel Flow (lb/hr)

From these signals additional signals formed in the signal processing section are:

- N_{HC} Corrected Rotor Speed (rpm)
- P_{3T}/P_{3S} Total to Static Compressor Pressure Ratio

- $\dot{N}_H$ Rotor Speed Acceleration Rate (rpm/sec)
- θ Speed Correction Factor for Inlet Temperature

The pertinent rate and range checks for the preceding signals are listed in the Software Specification (Appendix B).

2. FUEL CONTROL

Fuel flow is the one engine input which most drastically affects temperatures and thus the thrust level of the engine. Thus, tight control of engine fuel flow is absolutely necessary. The fuel control portion of the ATEGG control mode logic has four major responsibilities:

- Provide fuel flow necessary for engine starting
- Provide transient fuel flow limiting capability through acceleration and deceleration schedules
- Provide transient fuel flow limiting capability if engine limits are exceeded
- Provide steady-state fuel flow necessary to maintain a given thrust level

These four responsibilities interface as shown in Figure 8 and are discussed in detail under the following subheadings. Four of the signals, $W_{f_{Decel}}$, $W_{f_{Start}}$, $W_{f_{Accel}}$, and $W_{f_{Governor}}$, are fuel flow values subject to the indicated logic, while $W_{f_{Limiters}}$ is a subtractive adjustment to the output of the select low box if engine limits are exceeded. The final fuel flow, $W_{f_{Engine}}$, is rate limited and compensated through a lead or lag network if necessary.

a. Start

For starting the engine, the fuel control must provide the necessary fuel flow for light-off and smooth acceleration up to an engine idle condition. This capability must exist for all foreseen test cell conditions.

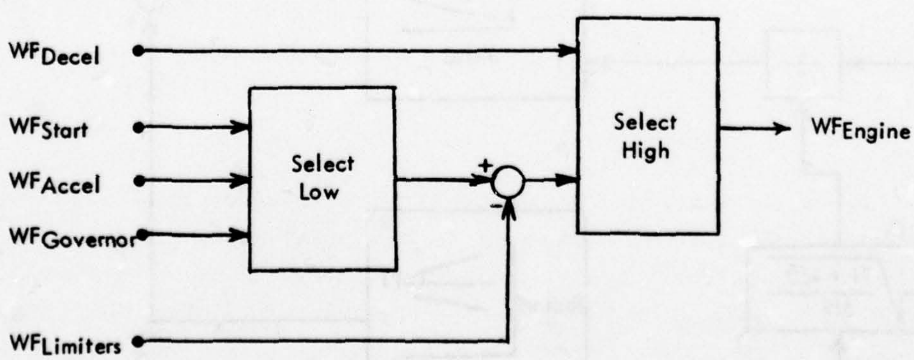

Figure 8. Fuel Flow Selection Logic.

Fuel flow modulation in the start region has been handled as simply as possible. A constant value of fuel flow is held for engine lightoff. From lightoff to engine idle, fuel flow is metered proportionally with respect to PLA. Both the lightoff fuel flow level and the gain of proportionality are programmable values. The engine start logic is disabled once idle speed is reached, and another area of the fuel control logic assumes responsibility for fuel modulation.

b. Acceleration/Deceleration

In order to protect the engine from damage during power excursions, acceleration and deceleration schedules exist. The acceleration schedule is implemented to provide fuel flow limiting for excursions from low to high power. The purpose of fuel flow limiting here is to avoid compressor surge. The deceleration schedule prevents lean blowout or an underfueling condition during excursions from high to low power.

The acceleration fuel flow, $W_{f_{Accel}}$, is the result of the logic shown in Figure 9. As can be seen, the acceleration fuel flow is a function of N_H, T_1, HPT, and P_3.

The primary schedule of N_{HC} vs W_f/P_3 provides two features: (1) tracking of engine dynamics through scheduling on N_{HC} and (2) aiding surge recovery through decreasing fuel flow to achieve the desired W_f/P_3 ratio for a sudden drop in P_3. The bias due to HPT allows surge protection in a region of constant speed operation. This is due to the fact that once 100% corrected gasifier speed is reached, the thrust level can feasibly be increased by increasing $T_{4.1}$. This constant speed $T_{4.1}$ range necessitates a range of required W_f/P_3 ratios. Since HPT is used to control $T_{4.1}$ (as will be explained later) and HPT changes monotonically with $T_{4.1}$ in this region, the

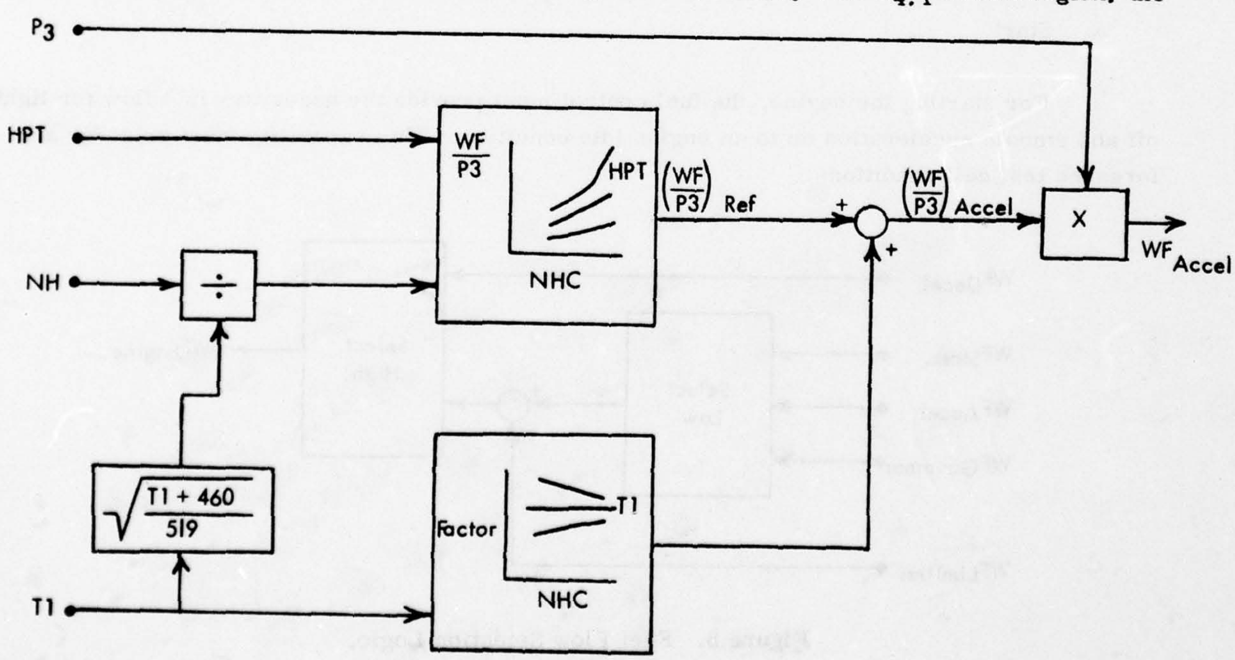

Figure 9. Acceleration Fuel Flow Logic.

HPT bias is useful for changing the W_f/P_3 reference ratio at 100% N_{HC}. T_1 is used to calculate corrected speed as well as provide an added bias on the desired W_f/P_3. P_3 is used as a multiplier to finally arrive at the desired $W_{f_{Accel}}$.

The deceleration fuel flow schedule is a single function relationship of N_{HC} vs W_f/P_3. This is less critical than the acceleration schedule, so no T_1 or HPT biases exist. As in the acceleration fuel flow logic, the W_f/P_3 reference is multiplied by P_3 to yield the desired deceleration fuel flow.

c. Limiters

A separate portion of the fuel control modes exists for the sake of decreasing the fuel flow command if particular engine limits are exceeded. The engine parameters requiring limiters are P_3, TBT, $T_{4.1}$, and P_{3T}/P_{3S}. All limiter circuits are of the form shown in Figure 10. A reference value is compared to a corresponding engine feedback signal. If a negative error results, indicating a limit has been exceeded, the error is compensated through gain and lead or lag, if necessary, and rate limited. The resulting fuel flow adjustment is passed into a select low circuit where the most restrictive of the limits is selected and its fuel flow adjustment becomes the $W_{f_{Limiters}}$ value in Figure 8.

In the case of P_3 and TBT, the reference values are absolute limits. In the case of $T_{4.1}$ the reference value is calculated through the following equation:

$$T4.1_{Ref} = T4.1_{Const} + K\,(HPT-16) + T_1/10$$

This is due to the fact that T_4 is actually the value which requires limiting, but since measurement of $T_{4.1}$ is reasonable and measurement of T_4 is not, an empirical relationship has been established relating $T4.1_{Ref}$ to an absolute T_4 limit through knowledge of HPT and T_1.

The P_{3T}/P_{3S} reference limit comes from a schedule of P_{3T}/P_{3S} vs N_{HC} biased by HPC as shown in Figure 11. This P_{3T}/P_{3S} ratio is an indication of compressor discharge Mach number. This relationship allows a correlation between P_{3T}/P_{3S} and compressor surge margin. This

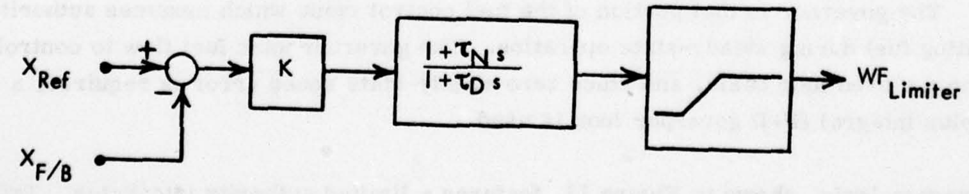

Figure 10. Typical Fuel Flow Limiter Logic.

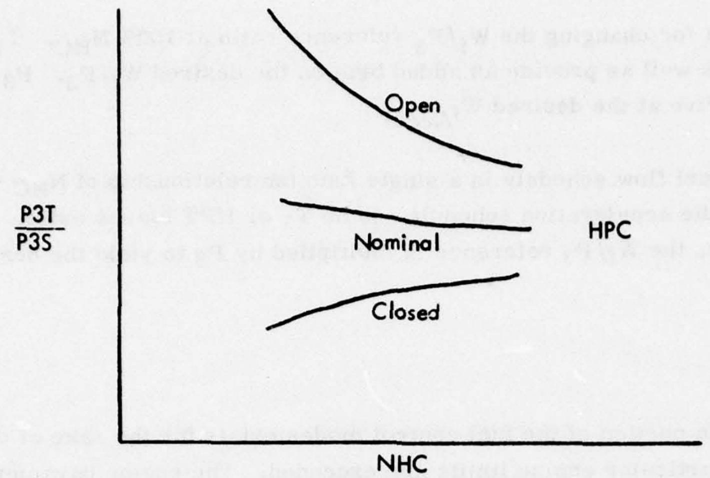

Figure 11. P_{3T}/P_{3S} Surge Control Schedule.

is useful in allowing fuel to be limited during an acceleration to maintain a given P_{3T}/P_{3S} and thus accelerate on a line of constant surge margin. Despite its appeal, the accuracy required on P_{3T}/P_{3S} to maintain reasonable control of surge margin is not feasible for given transducer accuracy. It is, therefore, desirable to substitute a schedule of $\Delta P/P_{3S}$ vs N_{HC} biased by HPC where

$$\Delta P = P_{3T} - P_{3S}$$

so that

$$\frac{\Delta P}{P_{3S}} = \frac{P_{3T}}{P_{3S}} - 1$$

Since a ΔP measuring device with the required accuracy and the capability of operating at compressor discharge has not been sufficiently developed, limited immediate use of this surge control mode is planned.

d. Governor

The governor is that portion of the fuel control mode which assumes authority for modulating fuel during steady-state operation. The governor uses fuel flow to control gasifier speed on a closed loop basis, and since zero steady-state speed error is required, a proportional plus integral (P+I) governor loop is used.

The governor logic, shown in Figure 12, features a limited authority integrator. This means that the integral channel acts as a "tweeker" to fuel flow and does not require winding up or down over a large range.

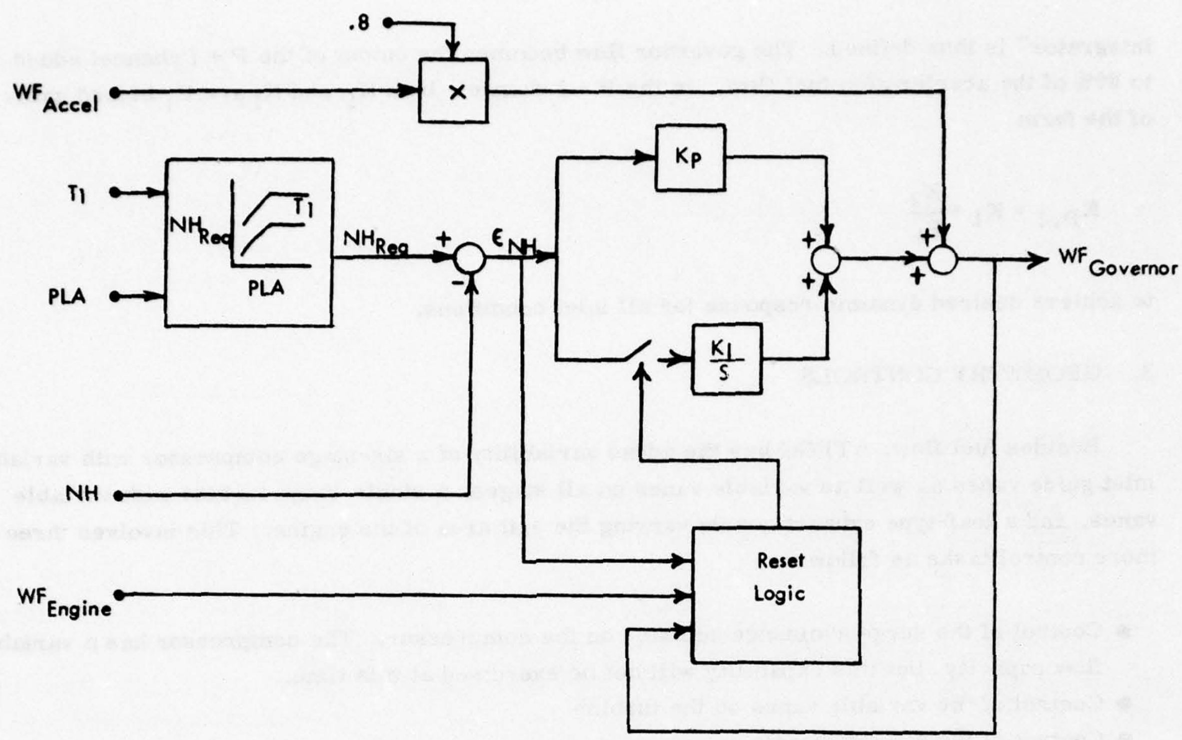

Figure 12. Governor Fuel Flow Logic.

The required gasifier speed is scheduled on PLA and biased by T_1. The speed error formed by the differences between the requested value and the feedback value is introduced to the P+I channel. The error is always passed through the proportional channel, but a switch at the input of the integrator controls whether the speed error is passed through the integral channel. The switch is controlled by the following reset logic:

if $W_{f_{Engine}} < W_{f_{Governor}}$ and $\epsilon_{N_H} \geq 0$

open switch

if $W_{f_{Engine}} > W_{f_{Governor}}$ and $\epsilon_{N_H} < 0$

The first of these tests is satisfied if the acceleration schedule or one of the engine limiters is in authority, while the second of these tests is satisfied if the deceleration schedule is in control. By opening the switch, the output from the integrator is "frozen." This, along with the fact that 80% of the acceleration fuel flow is used as the majority of the governor fuel flow, allows the integrator to operate over a limited range. The term "limited authority

integrator" is thus defined. The governor flow becomes the output of the P + I channel added to 80% of the acceleration fuel flow. In the P + I channel, both K_P and K_I are P_1 biased gains of the form

$$K_{P,I} = K_1 + \frac{K_2}{P_1}$$

to achieve desired dynamic response for all inlet conditions.

3. GEOMETRY CONTROLS

Besides fuel flow, ATEGG has the added variability of a six-stage compressor with variable inlet guide vanes as well as variable vanes on all stages, a single-stage turbine with variable vanes, and a leaf-type exhaust nozzle varying the exit area of the engine. This involves three more control tasks as follows:

- Control of the surge avoidance actuator on the compressor. The compressor has a variable flow capacity, but this capability will not be exercised at this time.
- Control of the variable vanes on the turbine
- Control of the exhaust nozzle

Care must be taken so that the geometries reach their desired steady-state positions without having an adverse effect on the transient response.

a. Compressor

As stated earlier, the compressor is a variable flow compressor with variable inlet guide vanes as well as variable vanes on each of its six stages. Actually, two actuators are necessary for movement of this compressor geometry. Figure 13 shows the relationship necessary for a nominal flow compressor setting to ensure surge-free operation. This actuator movement lends itself to an open loop schedule relationship.

The effect of the variable flow capability of the compressor is to move the fan-shaped form in Figure 13 vertically (as shown)—upward for a closed vane schedule or decreased flow capacity, or downward for an open vane schedule or increased flow capacity. This variable flow movement must thus be correlated with the surge avoidance mechanism. An actuation system to accomplish both of these compressor functions has not yet been designed. Thus, control of the variable flow capability will not be discussed here.

b. Turbine

The vane variability in the turbine allows a 23% variation in turbine flow capacity. This variation is accomplished over 5.5 degrees of total vane movement. This high sensitivity

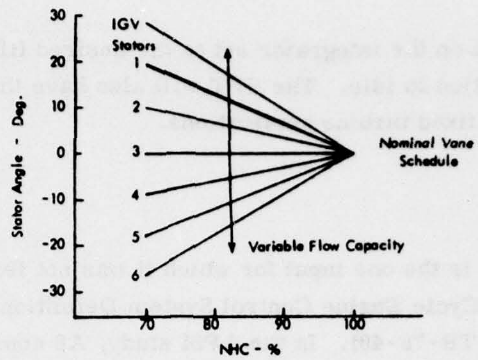

Figure 13. Compressor Surge Avoidance Relationship.

to vane modulation indicates the need for tight closed loop control of the turbine. The engine parameter $T_{4.1}$ has been chosen as the parameter to be controlled by HPT.

Figure 14 indicates the control logic required for the HPT portion of the control mode logic. The requested $T_{4.1}$, a T_1 biased request, is scheduled vs PLA instead of N_{HC} since $T_{4.1_{Req}}$ will change for different thrust levels in a constant speed range.

As in the case of the governor, an error is formed between the requested engine signal and the actual engine signal. The ability exists to compensate this error signal by a lead or lag network. During operation in the power region, this error is introduced to a P + I channel with the gains, as in the case of the governor, being P_1 compensated. The corresponding HPT request is then rate limited. The switch logic and the initial condition on the integrator exist for starting purposes as the HPT requires partially open position during engine starts. The switch opens if the gasifier speed is below idle and sets $\epsilon_{T4.1}$ to zero. Thus, with the switch

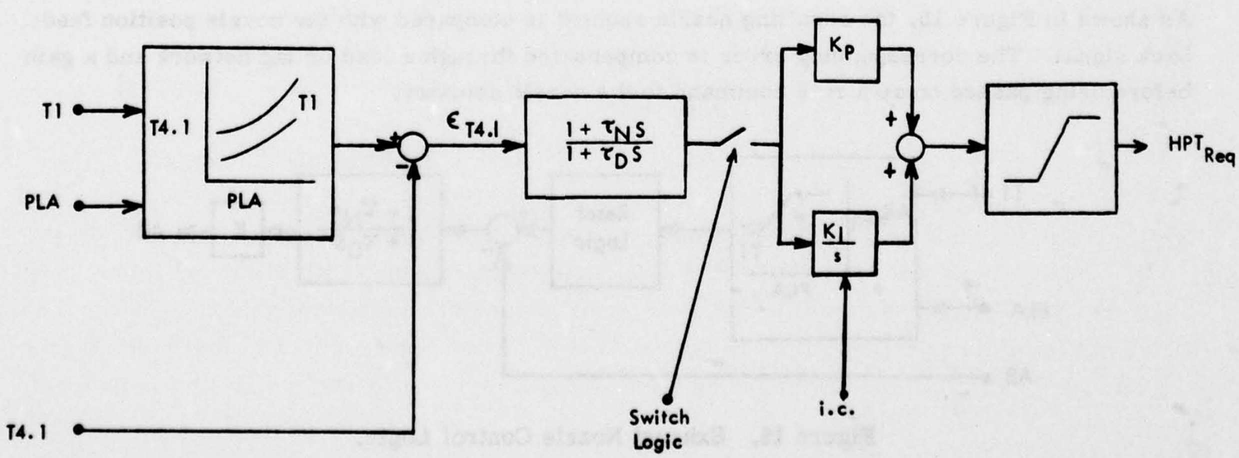

Figure 14. HPT Control Logic.

open and the initial condition on the integrator set to the desired HPT setting for starting. HPT will be held during acceleration to idle. The HPT will also have the capability for setting by operator request to execute fixed turbine applications.

c. Nozzle

The exhaust nozzle is the one input for which it was not feasible to control in the same manner as in the "Variable Cycle Engine Control System Definition Study," also referred to as the APSI study (ref AFAPL-TR-76-49). In the APSI study, A8 controlled the corrected fan rotor speed on a closed-loop basis. The absence of a low-pressure spool in this engine prompted an investigation into other possible control parameters. The present decision is to schedule A8 vs PLA. The schedule, as shown in Figure 15, is also T_1 compensated.

Due to the nature of the operating line selected, A8 remains open until 100% N_{HC} is reached. The reset logic overrides the scheduled $A8_{Req}$ value and sets $A8_{Req}$ to an open position if either of the following steps is satisfied:

$$P_T/P_S < (P_T/P_S)_{Ref}$$

or

$$N_{HC} < N_{HC_{Ref}}$$

The first of these is designed as a surge recovery aid so that if the error found in the surge control portion of the fuel limiter logic is less than zero, the nozzle moves in a direction as to give surge relief. Due to the present inability to accurately represent P_{3T}/P_{3S}, limited use of this switch is foreseen. The second test in the reset logic averts premature movement of the nozzle for large excursions from low to high power.

As shown in Figure 15, the resulting nozzle request is compared with the nozzle position feedback signal. The corresponding error is compensated through a lead or lag network and a gain before being passed on as a rate command to the nozzle actuator.

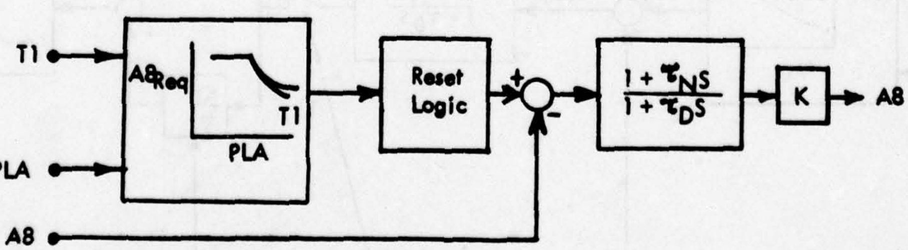

Figure 15. Exhaust Nozzle Control Logic.

4. SIGNAL SYNTHESIS

Use of the $T_{4.1}$ signal in the control logic offers the problem of a large time lag due to the thermocouple, plus the uncertainty of degree of accuracy due to swirl in back of the turbine. For this reason, some preliminary investigation was done on synthesizing a rotor inlet temperature effectively enough to use in a real time control application. The method chosen utilizes the fuel/air ratio in the burner as well as compressor discharge conditions to iteratively calculate the rotor inlet temperature. Successful implementation of such a method would allow fuel limiting and HPT control loop responsibilities to be carried on in the case of loss of the $T_{4.1}$ signal.

Figure 16 shows the method as characterized in the ATEGG logic. A heat balance is accomplished for the combustion chamber based on compressor discharge temperature, burner efficiency, fuel/air ratio, fuel conditions, and burner outlet temperature. Based on the heat balance, a burner outlet temperature can be calculated. As should be noted, the calculated burner outlet temperature is based on the previous burner outlet temperature, thus the iterative form of the problem. Since cooling air is introduced before the turbine rotor, another energy balance is accomplished to calculate rotor inlet temperature.

The disadvantage to the method is the necessity for accurate representation of airflow, a calculated relationship which depends upon the total-to-static pressure ratio at the compressor discharge. As stated earlier, this ratio as presently reproduced has not proved accurate enough for intensive use. Further refinement of this technique thus involves a more accurate representation of airflow.

5. SUMMARY

Figures 17 through 19 show the total control mode concept as it exists. These diagrams provide a summary of the previously described control logic. Schedules, gains, and compensation were initially established through extensive use of the non-linear simulation. Schedules have been revised per correlation with test stand data compiled from ATEGG Buildup No. 2 (BU2). Compensation and gain update have been established through feasibility testing at Bendix. This feasibility testing was accomplished using the implemented digital logic to control a linear analog model of the gas generator. This area will be discussed in the following two sections.

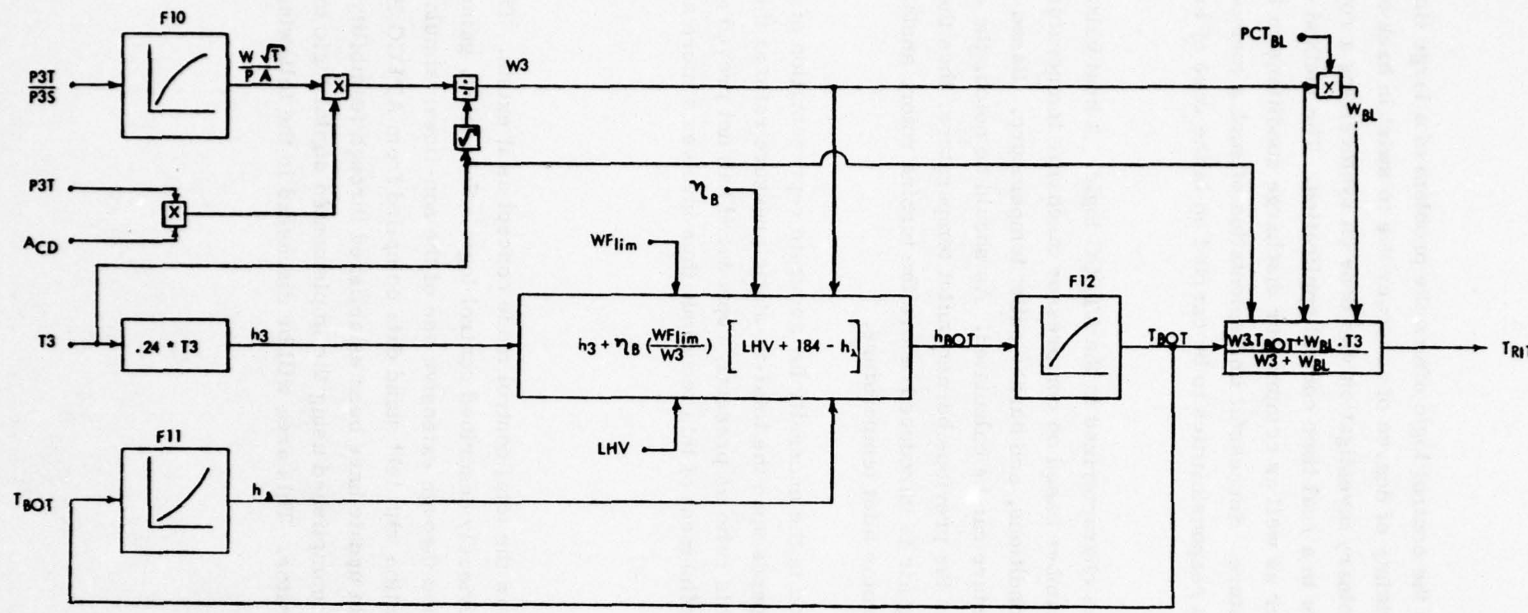

Figure 16. RIT Synthesis Logic.

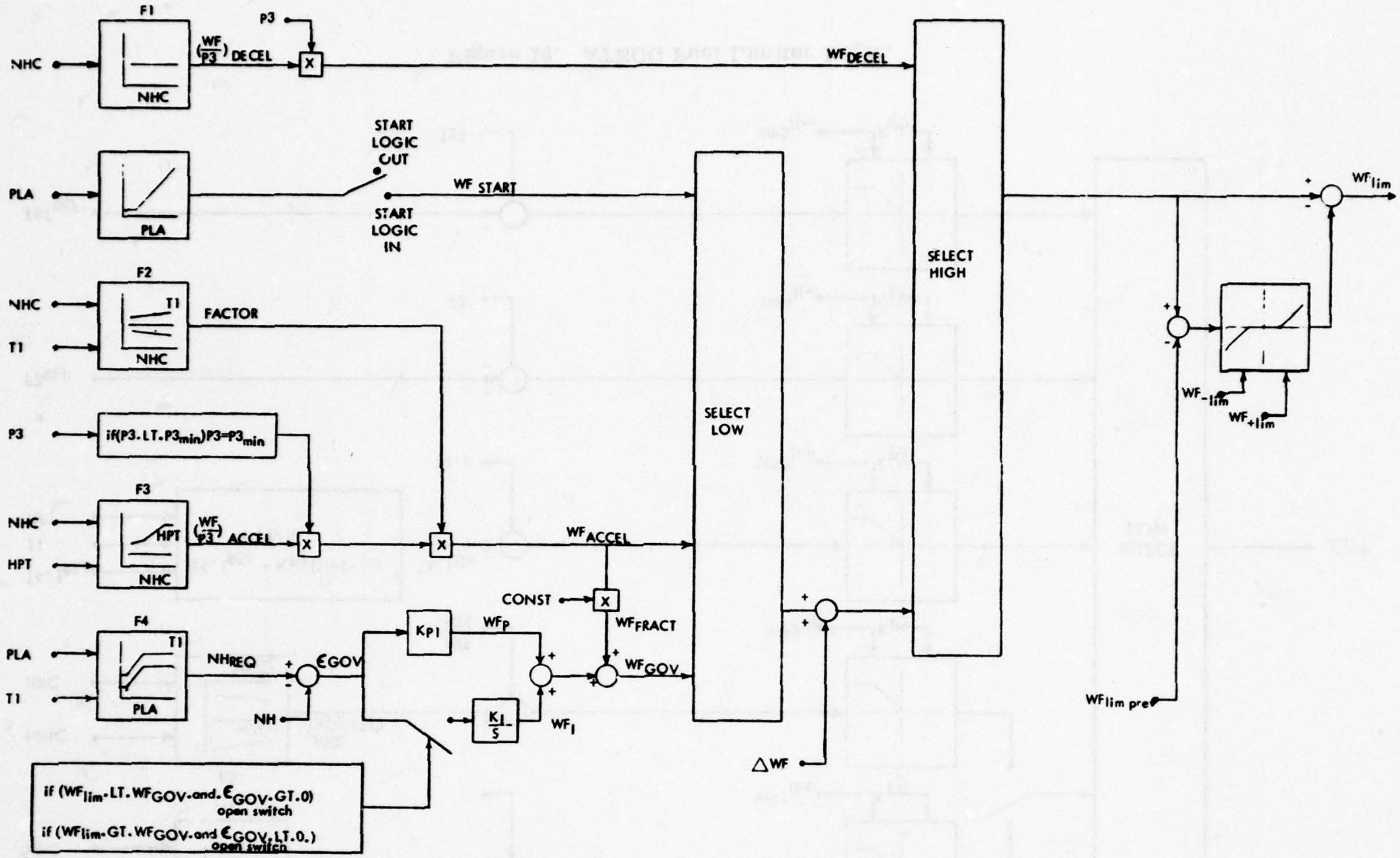

Figure 17. ATEGG Fuel Control Logic.

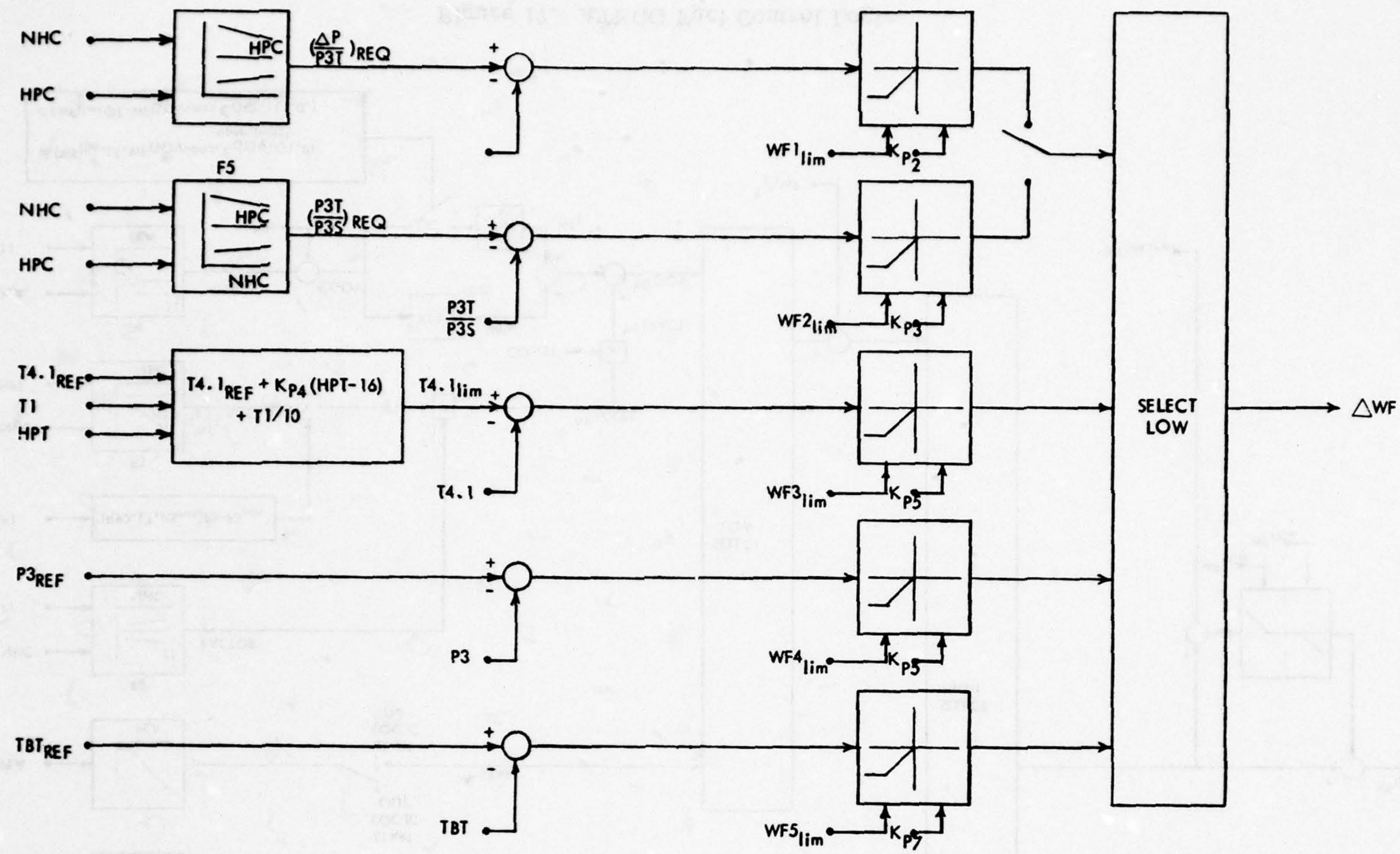

Figure 18. ATEGG Fuel Limiter Logic.

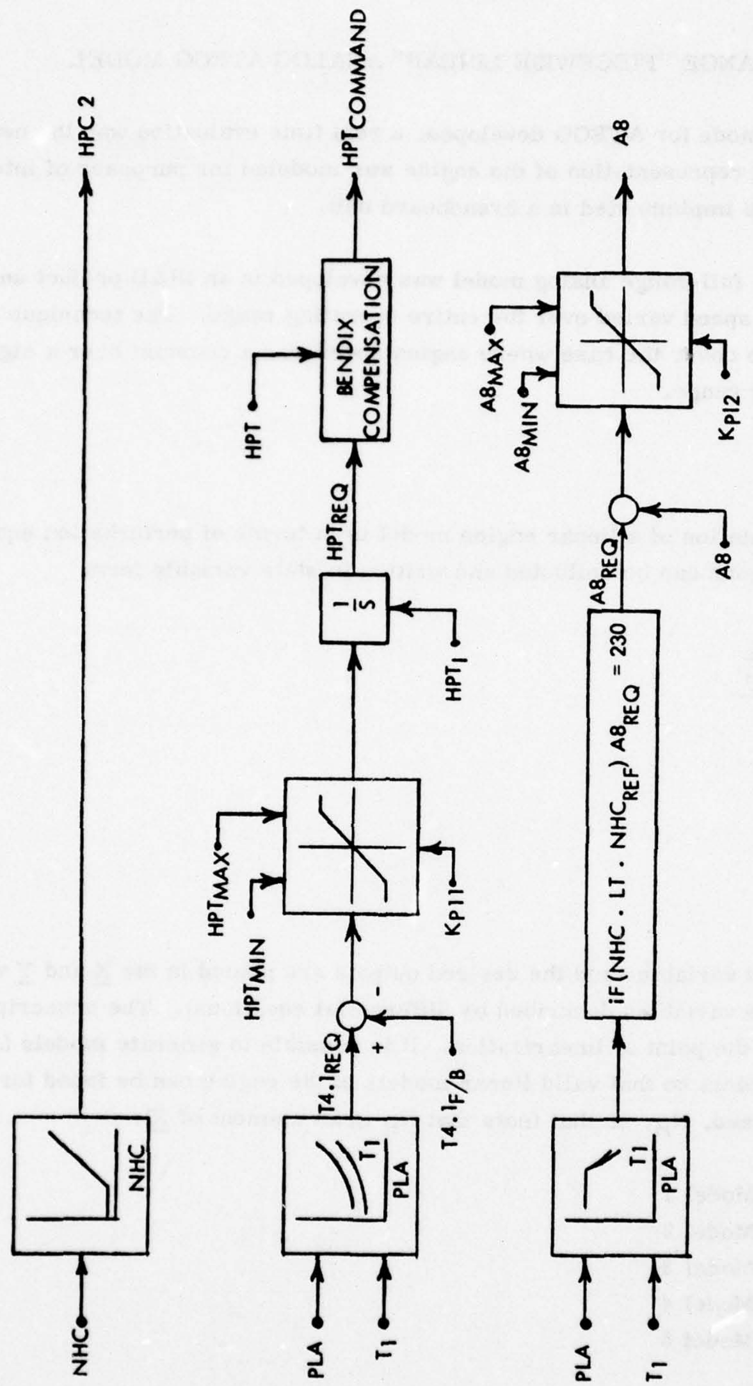

Figure 19. ATEGG Geometry Control Logic.

SECTION VI

FULL-RANGE "PIECEWISE LINEAR" ANALOG ATEGG MODEL

With the basic control mode for ATEGG developed, a real time evaluation was the next requirement. Thus, an analog representation of the engine was modeled for purposes of interfacing with the control logic as implemented in a breadboard unit.

The basic concept for a full-range analog model was developed in an IR&D project under the assumption that engine speed varied over the entire operating range. The technique was extended in this project to cover the case where engine speed was a constant over a significant portion of the operating range.

1. BASIC MODEL

A normal representation of a linear engine model is in terms of perturbation equations. The perturbation equations can be collected and written in state variable form

$$\delta \dot{\underline{X}} = A \ \delta \underline{X} + B \ \delta \underline{U}$$
$$\delta \underline{Y} = C \ \delta \underline{X} + D \ \delta \underline{U}$$

where

$$\delta \underline{X} = \underline{X} - \underline{X}_{Nom}$$
$$\delta \underline{Y} = \underline{Y} - \underline{Y}_{Nom}$$
$$\delta \underline{U} = \underline{U} - \underline{U}_{Nom}$$

$\underline{U}$ is a vector of control variables and the desired outputs are placed in the $\underline{X}$ and $\underline{Y}$ vectors (the $\underline{X}$ vector contains those variables described by differential equations). The subscript Nom denotes nominal value at the point of linearization. It is possible to generate models (A, B, C, and D) about several points so that valid linear models of the engine can be found for each of five ranges of rotor speed, N_H, so that (note that N_H is an element of $\underline{X}$):

Idle $\leq N_H < N_1$	Model 1
$N_1 \leq N_H < N_2$	Model 2
$N_2 \leq N_H < N_3$	Model 3
$N_3 \leq N_H < N_4$	Model 4
$N_4 \leq N_H \leq N_5$	Model 5

Then a full range transient can be generated in the following manner:

1) Determine the proper speed range and model for N_H at $t = 0$ and generate the transient response with the proper linear model until the speed exceeds the range for the model.

2) Continue the transient with the new model for the next speed range. This involves substituting new values for $\underline{U}_{Nom}$, $\underline{X}_{Nom}$, $\underline{Y}_{Nom}$ and the model coefficients A, B, C, and D.
3) Repeat this procedure until the final state is reached.

This simplified simulation has limited accuracy and yields discontinuities each time the model is changed. The accuracy can be improved by increasing the number of linear models. This concept can be carried to the point where the model varies continuously in digital form as shown in Figure 20(a) for the simple case where

$$\underline{X} = N_H$$
$$\underline{U} = W_f$$
$$\underline{Y} = 0$$

This concept assumes that the coefficients and nominal input values can be expressed as a function of N_H only over the range of interest and that the previous value of N_H becomes the present $N_{H_{Nom}}$.

Now, a very interesting thing occurs when the above model is changed to an analog model by letting $\Delta T \rightarrow 0$. Then $\Delta N_H \rightarrow 0$ and the feedback path with $\partial \dot{N}_H / \partial N_H$ disappears to yield the simple model shown in Figure 20(b).

2. APPLICATION TO ATEGG

Applying this concept to the ATEGG engine with its multiple input - multiple output structure, the vectors in the state variable form are:

$\underline{X}$ =	N_H	rotor speed*
$\underline{Y}$ =	P_3	compressor discharge pressure
	T_3	compressor discharge temperature
	$T_{4.1}$	turbine exit temperature
	W_3	compressor discharge airflow
$\underline{U}$ =	W_f	fuel flow
	HPC	compressor geometry position
	HPT	turbine geometry position
	A8	exhaust nozzle area

to yield the model shown in Figure 21.

*Because of the dynamic limitations of the nonlinear ATEGG model, speed is the only state variable.

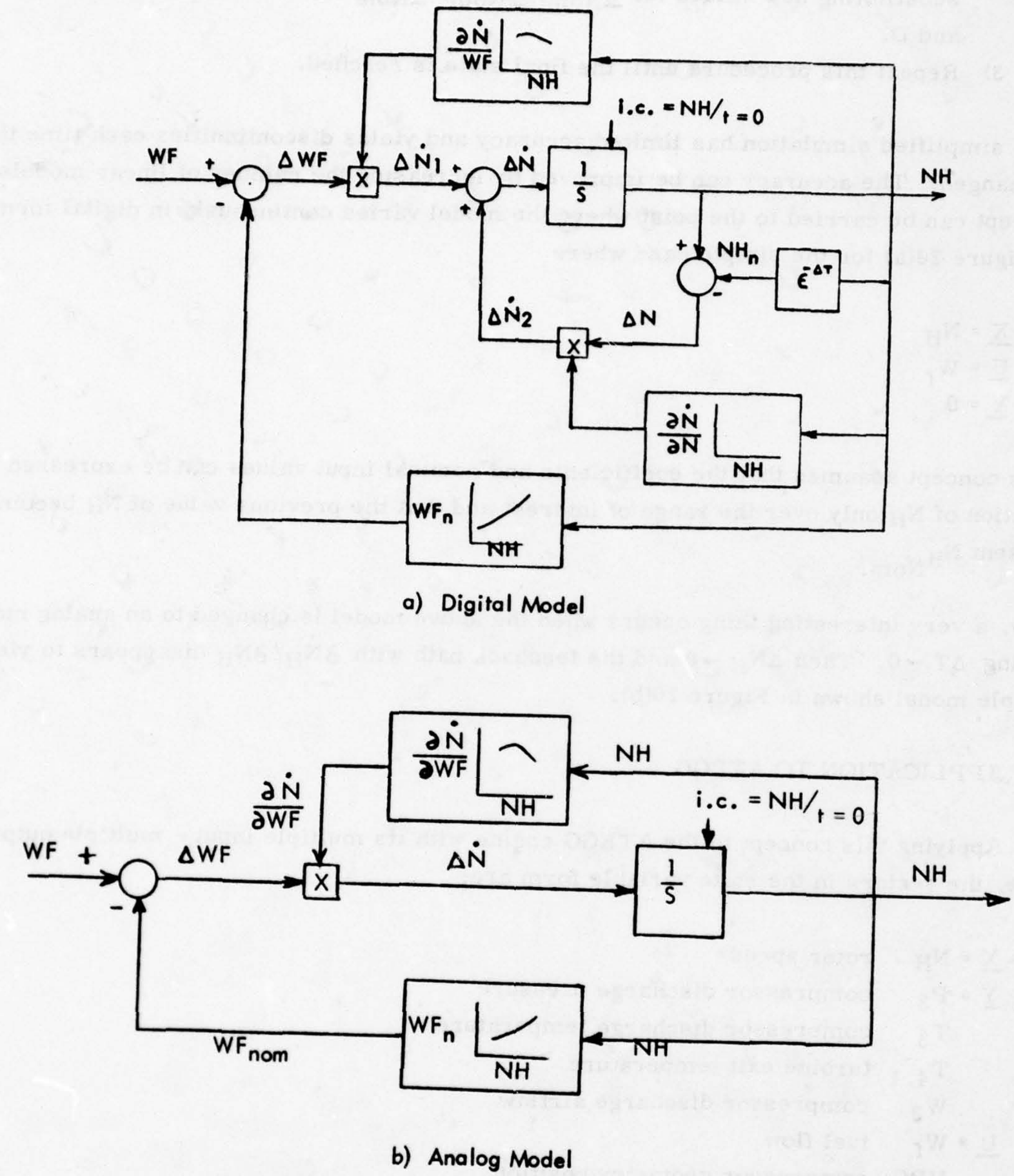

Figure 20. Piecewise Linear Model.

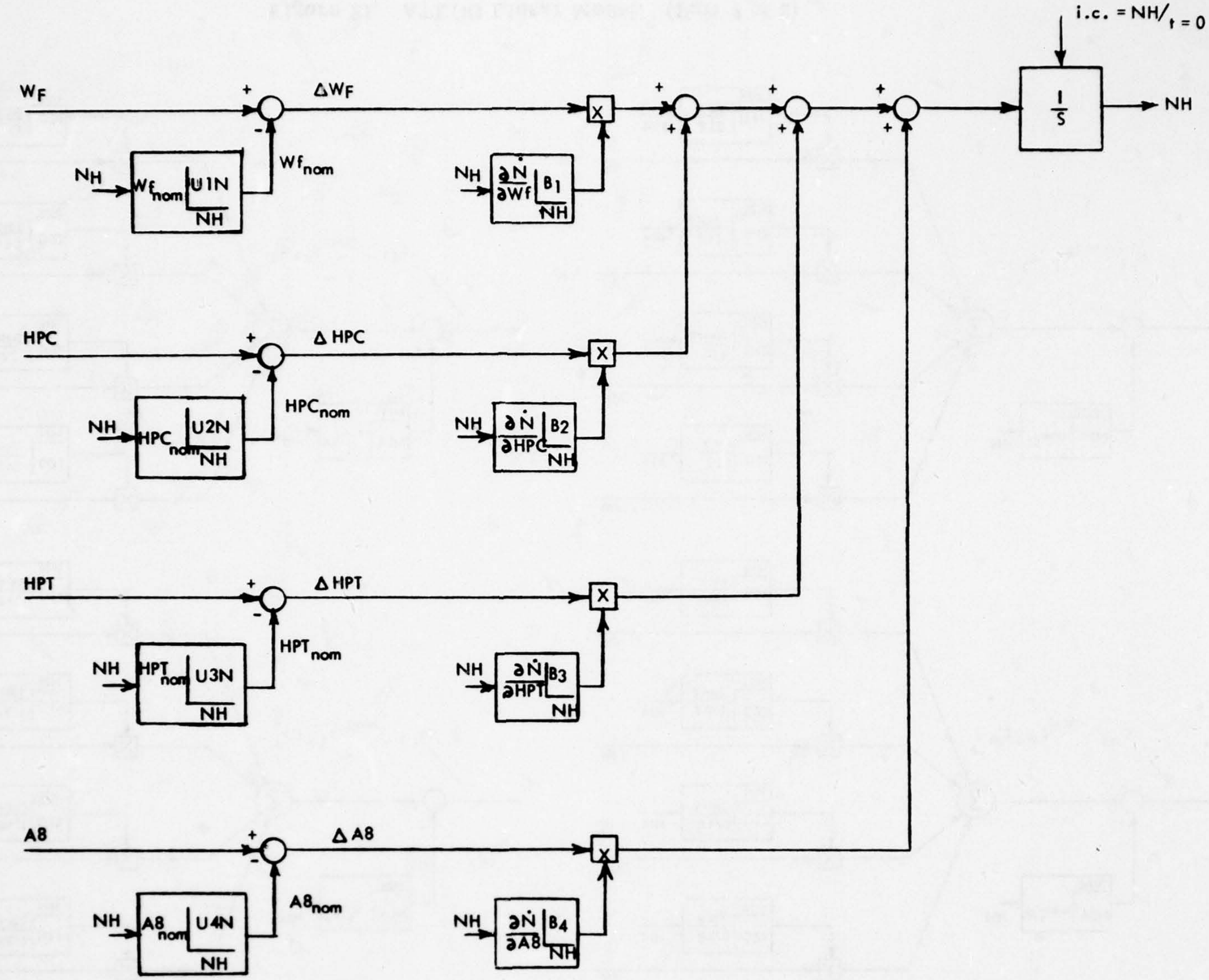

Figure 21. ATEGG Linear Model. (Part 1 of 2)

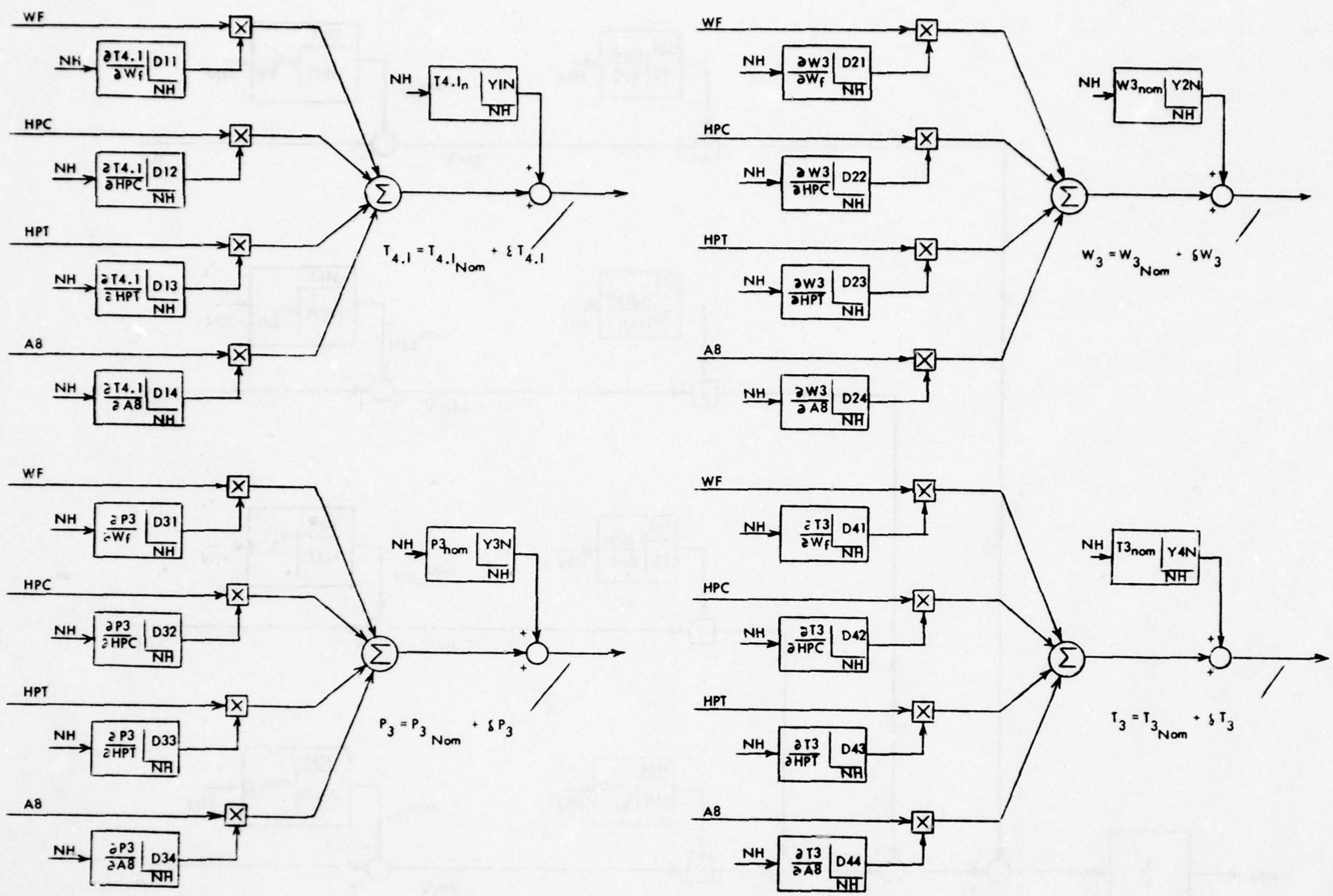

Figure 21. ATEGG Linear Model. (Part 2 of 2)

The coefficients of B and D were computed using the linear identification techniques developed under an IR&D project (note that the A and C matrices disappear in this model due to the floating nominal value). The ATEGG nonlinear digital simulation was used to generate transient responses to inlet stimulation of different magnitudes (±5%, ±10%, ±15%) about several operating points. Comparison of the coefficients for the three different stimuli showed little difference for the ±5% and ±10% perturbation but some significant changes between ±10% and ±15%. Thus, coefficients were chosen so that the linearization is valid for ±10% perturbations. This yields the coefficients in Table 1 for perturbations about steady-state points defined by the ATEGG control and the noted power lever angle (PLA) settings.

TABLE 1

NORMALIZED MODEL COEFFICIENTS

PLA	=	60°	63°	65°	66°	69°	72°	75°	79°	81°	85°	89°	93°
X1	=	74.1	75.8	82.3	83.8	88.3	92.3	96.0	100.0	100.0	100.0	100.0	100.0
U1N	=	881.0	934.0	1124.0	1197.0	1455.0	1718.0	1954.0	2274.0	2515.0	2961.0	3450.0	4017.0
U2N	=	86.0	91.0	91.4	91.7	92.1	94.0	94.4	107.8	110.0	110.0	110.0	110.0
U3N	=	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	110.0	110.0	110.0	110.0
U4N	=	230.0	230.0	230.0	230.0	230.0	230.0	230.0	230.0	216.0	196.0	178.7	165.7
Y1N	=	35.6	34.6	34.5	34.8	36.1	37.0	37.3	38.7	31.3	45.9	50.8	56.4
Y2N	=	21.5	23.9	28.6	29.9	33.9	38.2	42.4	46.3	46.3	46.3	46.4	46.3
Y3N	=	39.1	43.2	52.6	55.5	64.6	74.5	84.0	94.0	93.9	94.0	94.3	94.0
Y4N	=	737.3	755.9	802.4	815.2	855.0	892.3	924.8	936.4	964.1	964.9	966.8	964.8
B1	=	0.160	0.170	0.200	0.205	0.210	0.220	0.260	0.280	0.2870	0.3146	0.2838	0.2799
B2	=	-0.150	-0.160	-0.240	-0.240	-0.250	-0.200	-0.150	-0.110	-0.0992	-0.1180	-0.0692	-0.0411
B3	=	-0.078	-0.090	-0.110	-0.120	-0.180	-0.220	-0.260	-0.200	-0.1767	-0.1847	-0.1231	-0.0576
B4	=	0.045	0.070	0.075	0.080	0.080	0.080	0.100	0.200	0.1327	0.2149	0.3200	0.4182
D11	=	0.530	0.530	0.530	0.530	0.540	0.545	0.550	0.580	0.5732	0.5804	0.5843	0.5998
D12	=	-0.610	-0.530	-0.440	-0.440	-0.380	-0.350	-0.460	-0.240	0.0404	0.0720	0.0815	0.0698
D13	=	-0.020	-0.040	-0.021	-0.030	-0.038	-0.021	-0.014	-0.020	0.0572	0.0753	0.0698	0.4370
D14	=	-0.040	-0.040	-0.048	-0.043	-0.030	-0.030	-0.170	-0.120	-0.0567	-0.0481	-0.0684	-0.1041
D21	=	-0.056	-0.057	-0.076	-0.080	-0.070	-0.061	-0.043	-0.020	-0.0184	-0.0120	0.0194	0.0207
D22	=	1.160	0.980	0.880	0.840	0.750	0.650	0.60	0.100	-0.0104	-0.0538	-0.0962	-0.0927
D23	=	0.110	0.140	0.120	0.115	0.110	0.070	0.150	0.120	0.0357	-0.0004	-0.0351	-0.0356
D24	=	0.004	0.000	0.001	-0.006	-0.007	-0.060	0.100	0.100	-0.0004	-0.0386	-0.0459	-0.0134
D31	=	0.180	0.170	0.140	0.121	0.180	0.180	0.180	0.200	0.2044	0.2243	0.2571	0.2625
D32	=	0.850	0.650	0.540	0.500	0.600	0.460	0.400	0.300	0.0110	-0.0187	-0.0487	-0.0401
D33	=	-0.270	-0.270	-0.300	-0.310	-0.260	-0.270	-0.200	-0.200	-0.3671	-0.4449	-0.4368	-0.3262
D34	=	0.020	0.007	-0.010	-0.020	0.040	0.003	0.190	0.160	-0.0008	-0.0275	-0.0253	0.0035
D41	=	0.055	0.060	0.046	0.046	0.060	0.060	0.054	0.050	0.0388	0.0326	0.0455	0.0506
D42	=	0.230	0.150	0.122	0.130	0.155	0.130	0.153	0.080	0.0675	0.0805	0.0699	0.0587
D43	=	-0.080	-0.085	-0.090	-0.080	-0.080	-0.080	-0.080	-0.085	-0.0872	-0.0930	-0.0852	-0.0439
D44	=	0.010	0.001	-0.003	-0.003	0.010	0.008	0.010	0.100	0.0108	-0.0034	0.0001	0.0088

A major problem is obvious from this table—the speed (X1) is a constant for PLA ≥79° (note: PLA = 60° is idle; PLA = 95° is intermediate power) while many of the nominals and coefficients vary for PLA ≥ 79°. Thus, it will not be sufficient to plot the nominals and coefficients as a function of speed alone to achieve full range operation.

3. EXTENSION OF MODEL TO CONSTANT SPEED REGION

A parameter other than speed is required to determine the model parameters for PLA $\geq$ 79°. The parameters W_f, HPT, A8, and $T_{4.1}$ in the simulation do vary over this range whereas the compressor and its related parameter are nearly constant in this control mode. In fact, for all running through Build 6, the HPC will be fixed and the extension of the model presented here assumes a fixed HPC. With the proposed ATEGG control mode, only A8 is not a function of engine parameters (open loop scheduled). Thus, the use of any parameter other than A8 to schedule engine simulation parameters would create complicated feedback paths between the control and simulation and potential simulation stability problems.

The extra parameter, A8, could be introduced by making the coefficients a function of two variables (N_H and A8) or introducing a bias computed as a function of A8 in the constant speed region only. The bias technique shown in Figure 22 was used to eliminate multi-function generation in the analog simulation. In addition, a transition area is provided to eliminate discontinuities when constant speed (NHCON) is reached and A8 is not at the nominal value.

Extending this concept to the total ATEGG model with a fixed HPC yields the model shown in Figure 23.

4. SUMMARY

Three models have been referenced to this point. The full-scale nonlinear digital simulation discussed in Section IV is used as described in Section IV.2.a. Various points are selected along the steady-state operating line and denoted as nominal operating points. The control variables are perturbed from their nominal values, thus resulting in time histories of these control variables in addition to time histories of the engine variables reacting to these control perturbations. Using an automatic parameter identification technique on these time histories results in linear engine models, one for each operating point, as represented in Section VI.1. By scheduling these models vs engine speed, the piecewise linear model shown in Figure 21 can be created. This model is adaptable to real time, but it is still not full range due to the nature

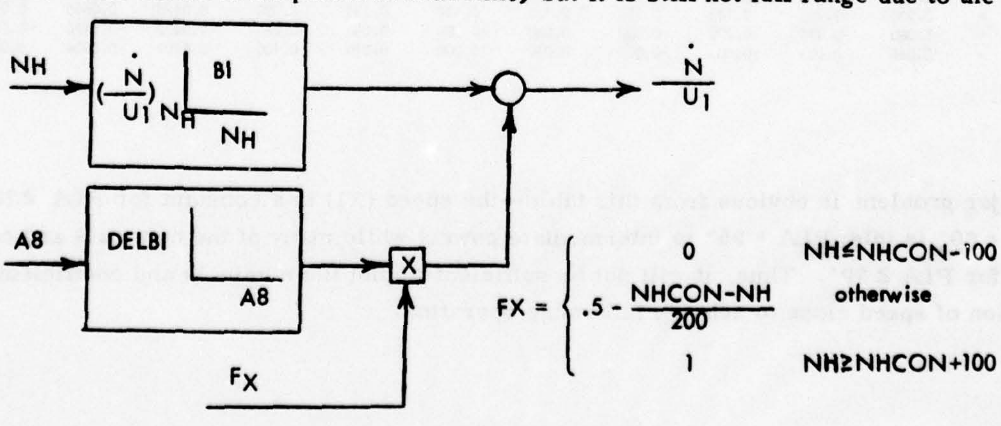

Figure 22. A8 Bias Method.

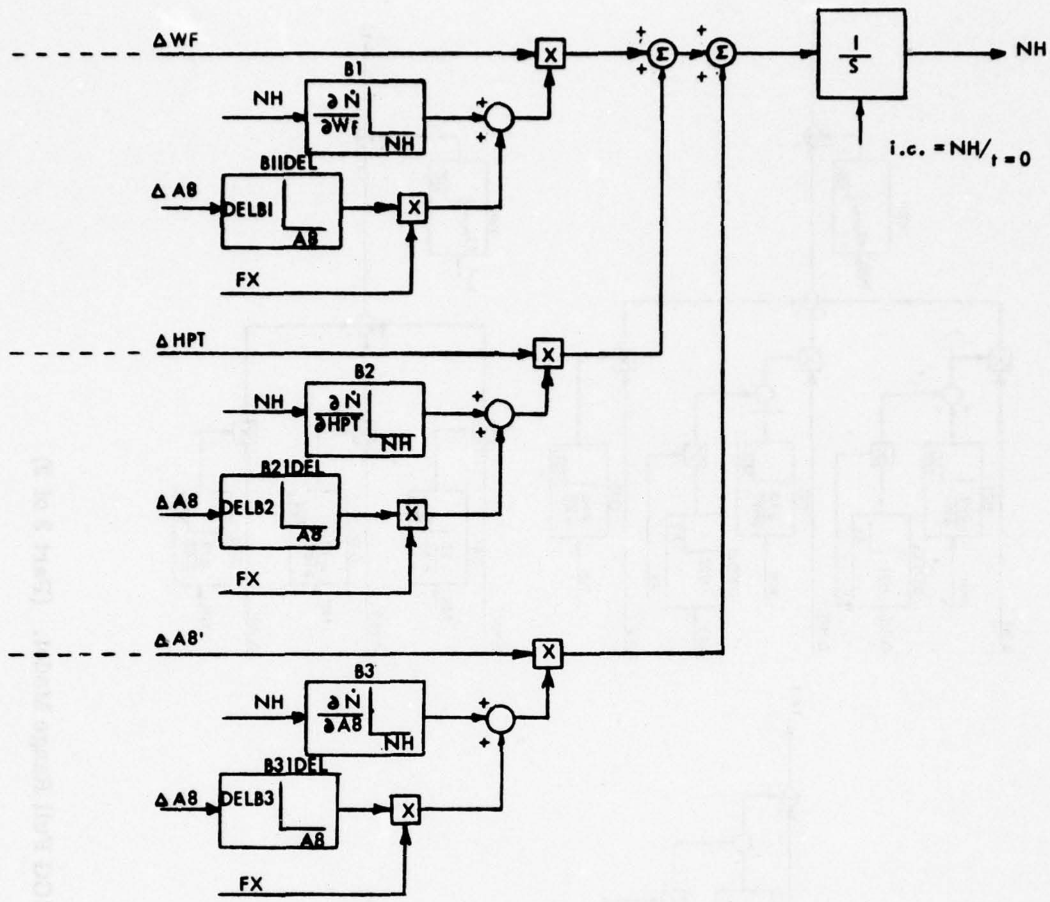

Figure 23. ATEGG Full Range Model. (Part 1 of 2)

of the operating line with its constant speed range. Thus, by biasing the model with A8, the only control parameter which is scheduled and not closed loop controlled, a full range representation as shown in Figure 23 results. It is this model which is desired for full range real time evaluation of the control logic. The model can be easily expanded to accommodate a variable HPC. HPC would be added in a manner similar to HPT. As mentioned previously, however, HPC was deleted for purposes of model simplification since all builds through ATEGG BU 6 are to be run with a fixed HPC.

A digitally mechanized version of the full range model was compared with the transient version of the nonlinear simulation for various controlled accelerations and decelerations. The maximum errors between the two of 1.2% on N_H and 5% on the other variables was considered acceptable for feasibility studies. However, such a model, if implemented on an analog computer,

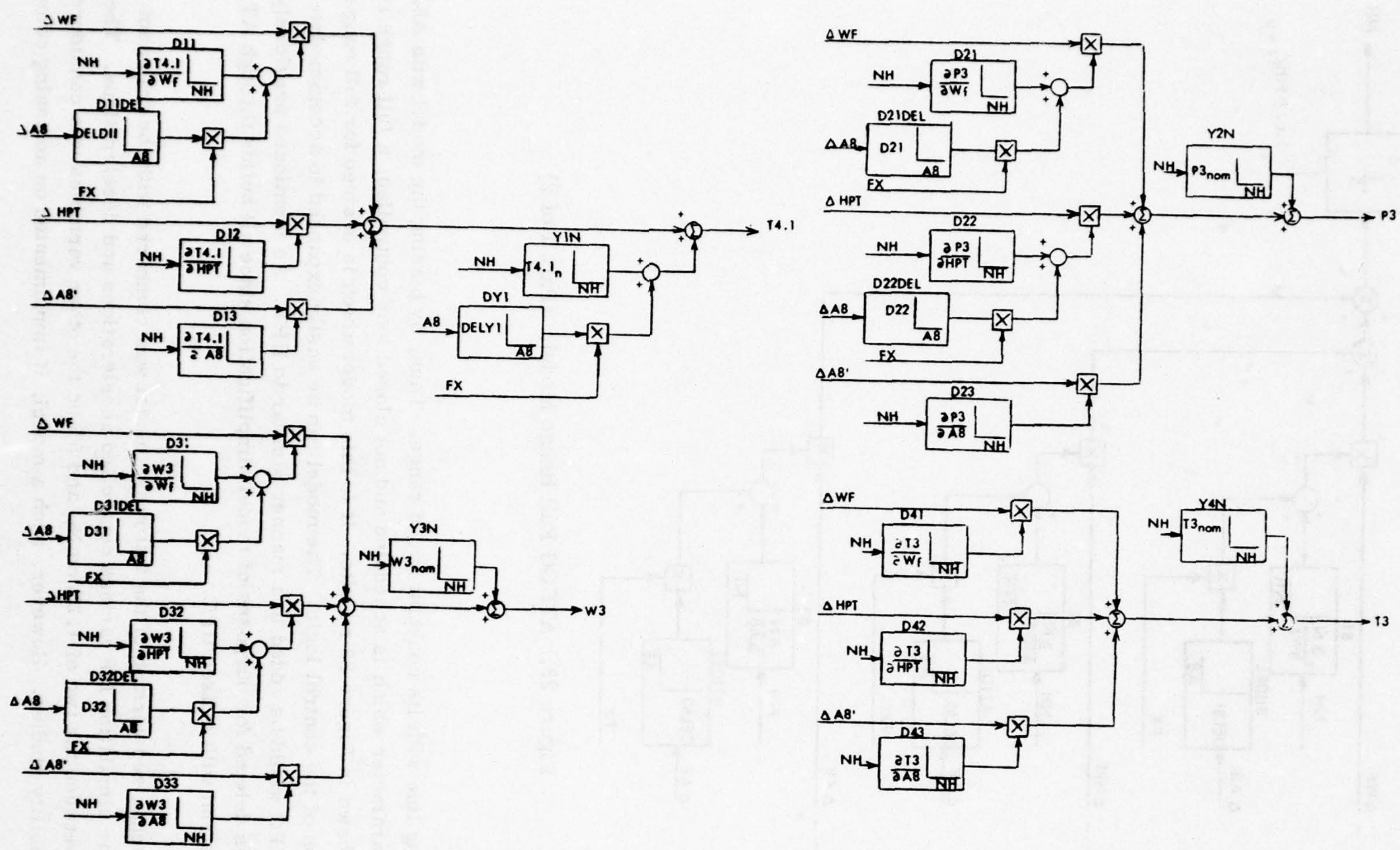

Figure 23. ATEGG Full Range Model. (Part 2 of 2)

requires more equipment than available. Thus, simplification for purposes of the feasibility test became necessary. Preliminary investigation concluded that since no coupling exists between the Y's in the engine model, any of these variables can be eliminated. Further simplification will be discussed in the feasibility test section (Section VII).

SECTION VII

ATEGG CONTROL SYSTEM FEASIBILITY TEST

The purpose of the feasibility test was to demonstrate that EH-K1 control software corresponding to the control modes developed functions correctly in both transient and steady-state conditions. The approach was to test the software on a real-time test system comprising an analog engine model, analog actuator and sensor models, and digital controller hardware (Figure 24).

The real time linear and nonlinear engine models based on linear model data provided by DDA were simulated on the Bendix PACE Model 231R and 631R analog computers. Models of sensor and actuator elements were added to the analog simulation with voltages scaled to provide actual parameter values at the software/hardware interface. Breadboard circuitry of the EH-K1 was used to interface the analog computer with the BDX-9000 digital computer. Simulated pressure signals were read in as voltages on spare analog interface channels. The control software executing on the BDX-9000 is, with minor modifications, the software for the EH-K1 controller and was coded in accordance with specifications for control solution rate, control mode, reasonableness checks, and failure action.

1. DESCRIPTION OF SYSTEM

a. Control

Figure 25 depicts the control logic programmed in the BDX 9000 and how it interfaces with sensed signals (inputs) and actuators (outputs). The control mode is implemented as

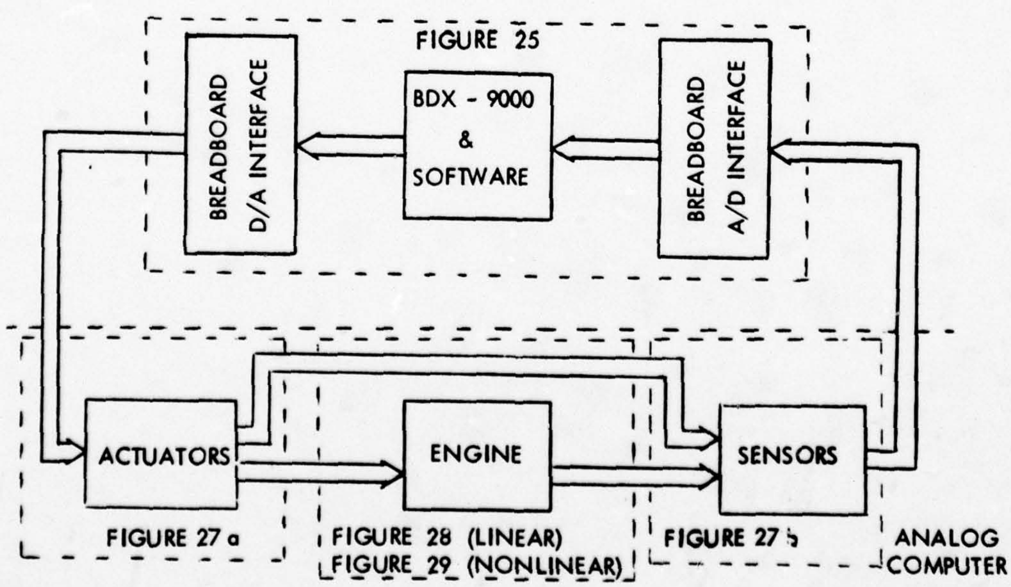

Figure 24. Real-Time Software Test System.

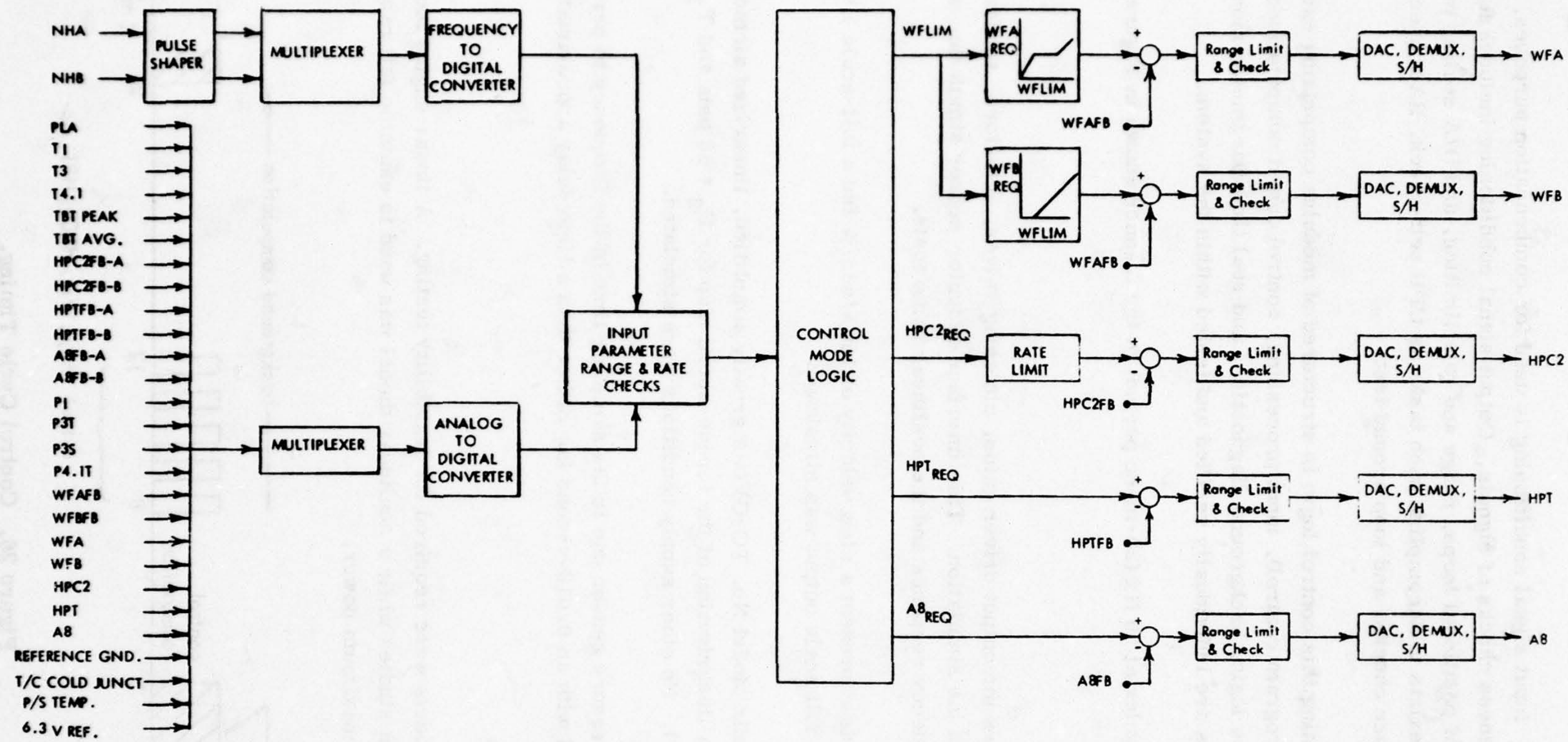

Figure 25. Feasibility Test Control Mode.

developed in Section V. Input signal conditioning is used for compensation purposes, A/D scaling, and reasonableness checks of signals. Output signal conditioning includes fuel flow splitter logic, closing of positional loops, range and rate limiting, and D/A scaling purposes. In addition, fault logic exists to accomplish such tasks as CPU self-check, RAM check, memory sumcheck, start sequence checks, and loop around test.

The software implementing this control logic is structured of modules comprising executive functions (timing and program control), input processing, control output computations, fault monitoring and response logic, background diagnostics, and real time parameter monitoring functions. The modules are individually verified and tested within the system.

The control program cycles at 50 Hz (20-msec period) in the manner shown in Figure 26.

b. Interface

Figure 27 shows the output driver gains, metering valves, actuators, sensors, and feedback scaling used in the simulation. This interface-actuator-sensor simulation was used for both the linear frequency response and the nonlinear ramp tests.

The metering valve gains represent a slew velocity of 150%/sec/% and a full-scale LVDT output of 0.15 volt. 1.2 volts full scale output was simulated.

The HPT actuator (Bendix Model No. TO-G) is a greatly simplified, linearized airmotor. The values used represent a linearization of the torque-speed map for P_3 = 66 psia and T_3 = 1200°R (hot inlet, PLA = 68.2°). No other supply conditions were simulated.

The dynamics of the pressure sensor due to the sampling time of the frequency to period conversion were simulated with an 0.018-second lag rather than a time delay approximation.

c. Engine Models

Two engine models were required for feasibility testing. A linear engine model was used for about-the-point studies while a nonlinear model was used to examine full range excursions between idle and maximum power.

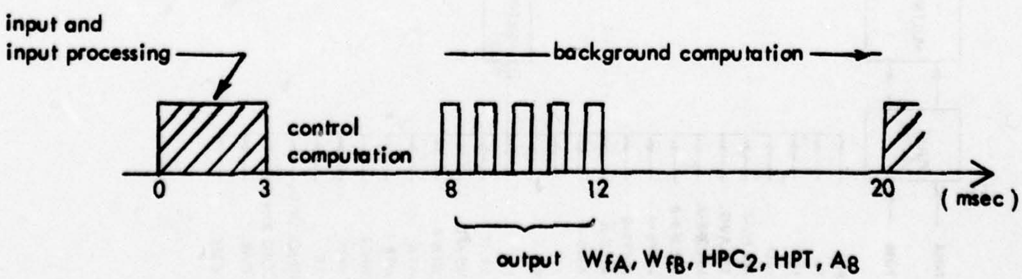

Figure 26. Control Cycle Timing.

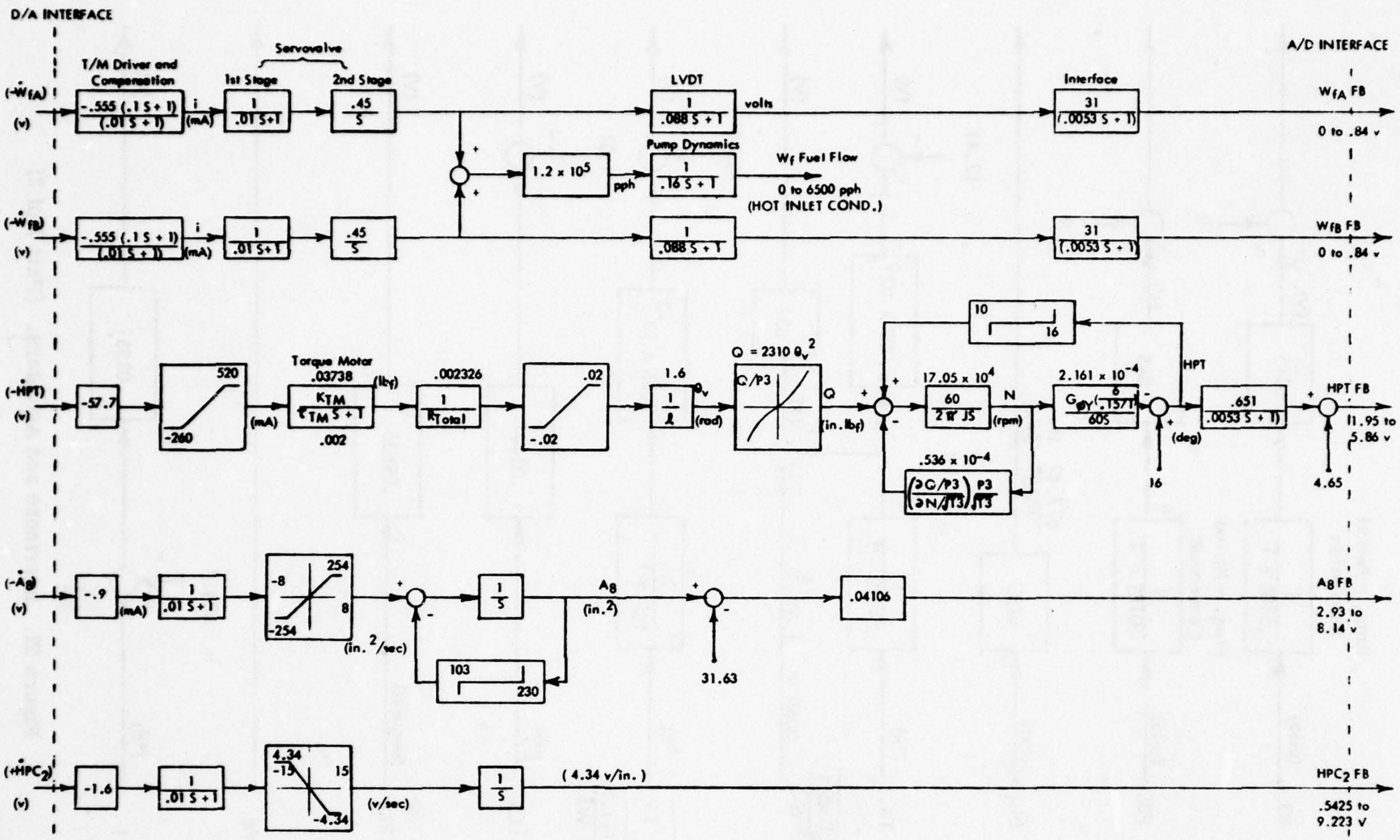

Figure 27. Interfaces and Actuators. (Part 1 of 2)

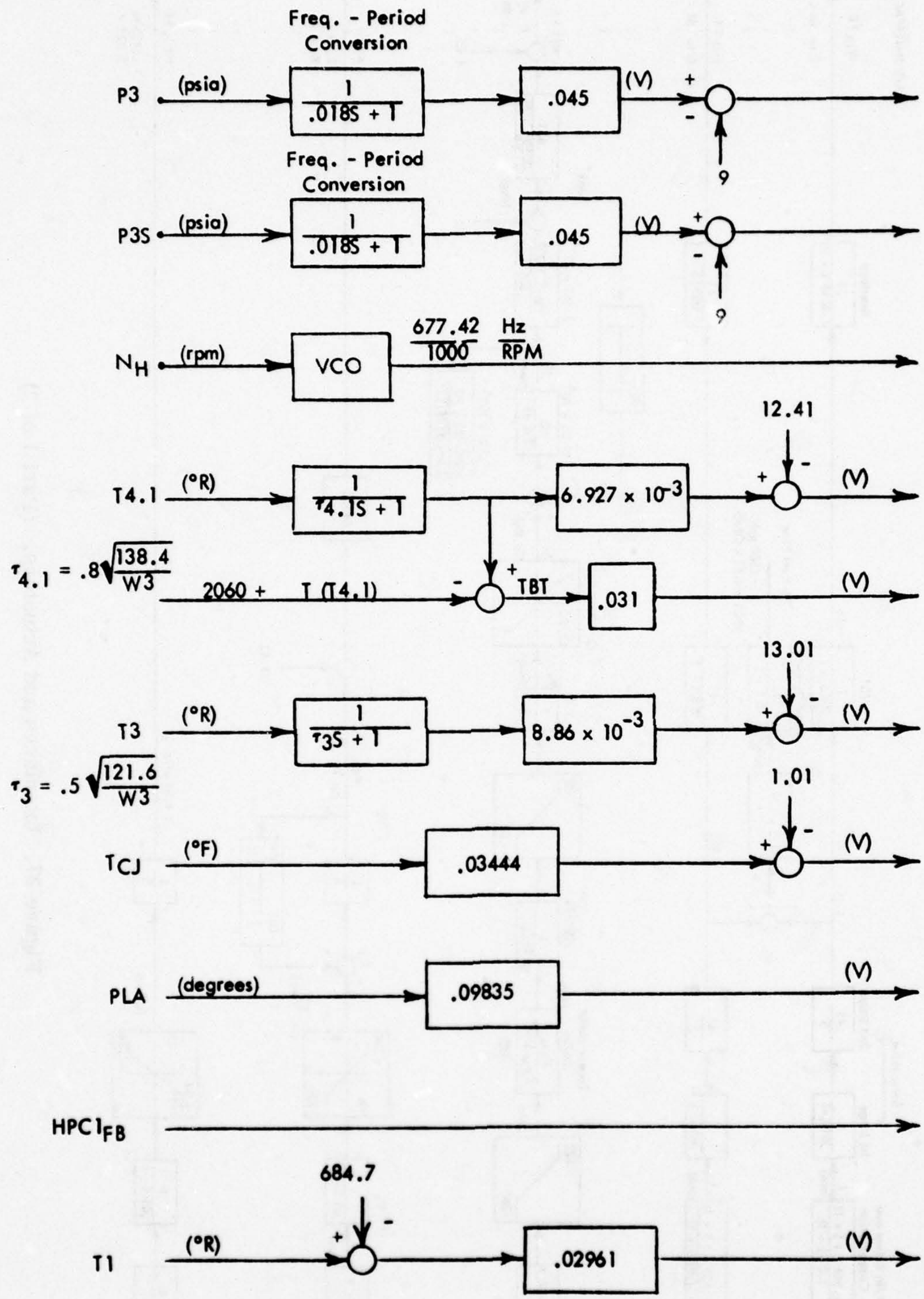

Figure 27. Interfaces and Actuators. (Part 2 of 2)

(1) Linear Engine

The linear engine simulation of Figure 28 was used for frequency response testing. This model, representing the form of the model discussed in Section VI. 1, utilizes two control variables (W_f and HPT), one engine state (N_H), and two outputs (P_3 and $T_{4.1}$). The model assumes a fixed A8 and HPC_1. Values for the partials were derived from the values listed in Table 1.

(2) Nonlinear Engine

Figure 29 represents the nonlinear engine simulation used for ramp tests between idle and maximum power. The simulation is basically a linear model with variable gains. Linear gains (refer to Table 1) which were changing significantly were scheduled as a function of speed through the variable speed region. The partial of $\dot{N}_H$ with respect to area (A8) is included so that in the constant-speed regime the area upset is balanced by the control action changing fuel flow and high-pressure turbine geometry. This allows the control to move up to the maximum power values of fuel flow and HPT.

The values used in the hot inlet simulation are shown in Table 2. Steady-state W_f versus N_H is 80% of the steady-state acceleration curve. The temperature versus speed relationship is a result of a crossplot of speed request and temperature request scheduled in the control. This curve was carefully adjusted so that the system would settle with near-zero W_f and HPT errors in the nonlinear engine simulation when operating in the variable speed region.

2. DISCUSSION OF DATA AND RESULTS

Figures 32 through 39 present typical results of the feasibility test at the hot, unrammed inlet condition. The control gains are the values sized by linear analysis except for the $T_{4.1}$ and HPT gains which were increased to prevent one unstable point identified during testing.

a. Frequency Response

Frequency response was run on all control loops using the linear engine simulation. A summing junction was added to the loops before the A/D interface, as shown in Figure 30. A frequency response analyzer was used which reduces from the forcing function to one signal (a), the forcing function to another signal (b), and divides the result which gives the response between the two signals (b/a). This technique is possible because the simulation has no large nonlinearities and a generally good signal-to-noise ratio. In this manner it is possible to check the open loop characteristics of the system running as a closed loop. Also because there are no dynamics between the forcing function and the A/D converter and in the digital feedback portion of the loop, closed loop response of the actuators could be run by reducing between the forcing function and the actuator position. Forcing function amplitudes were kept small to avoid rate limits, accel, decel and other nonlinearities.

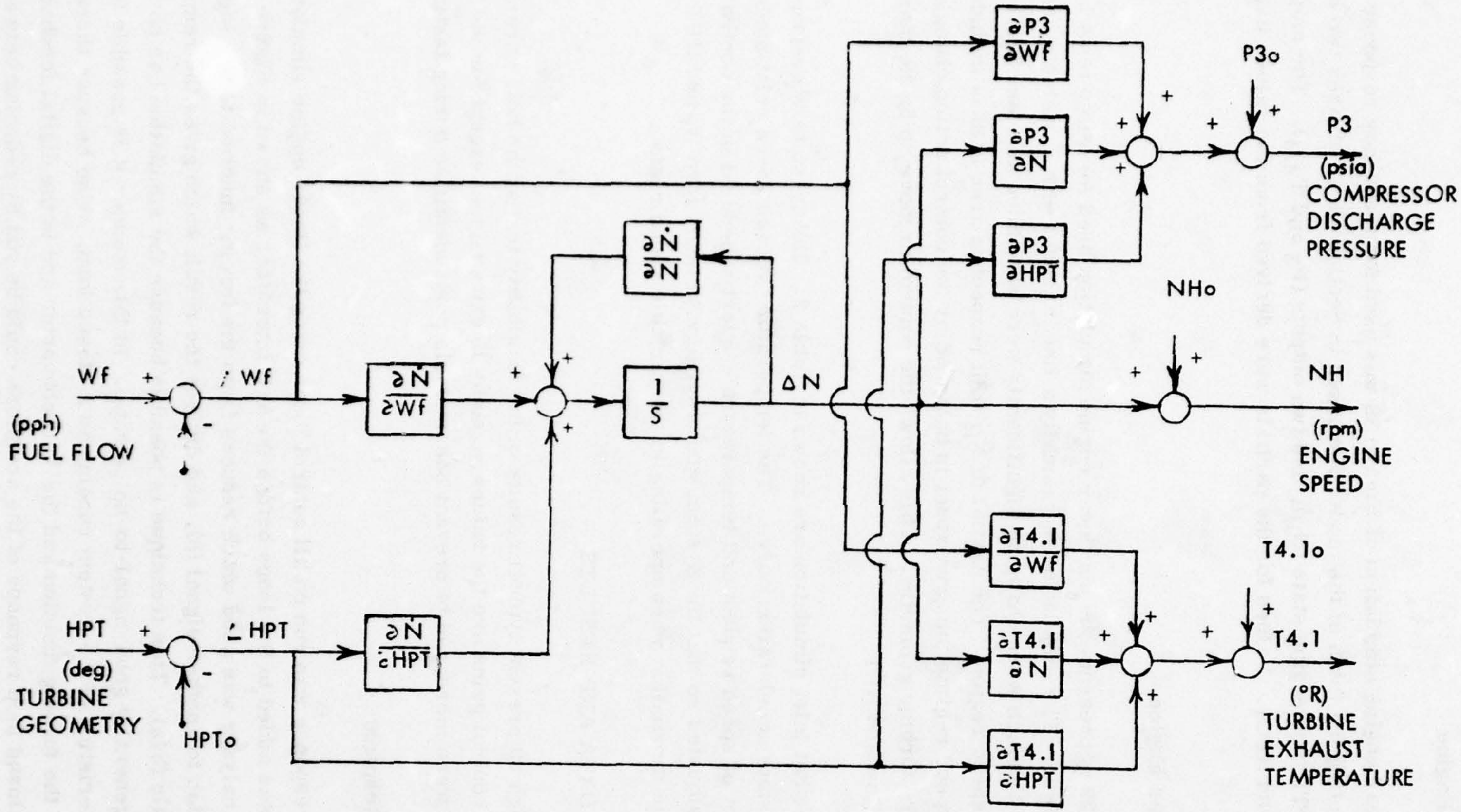

Figure 28. Linear ATEGG Engine Model.

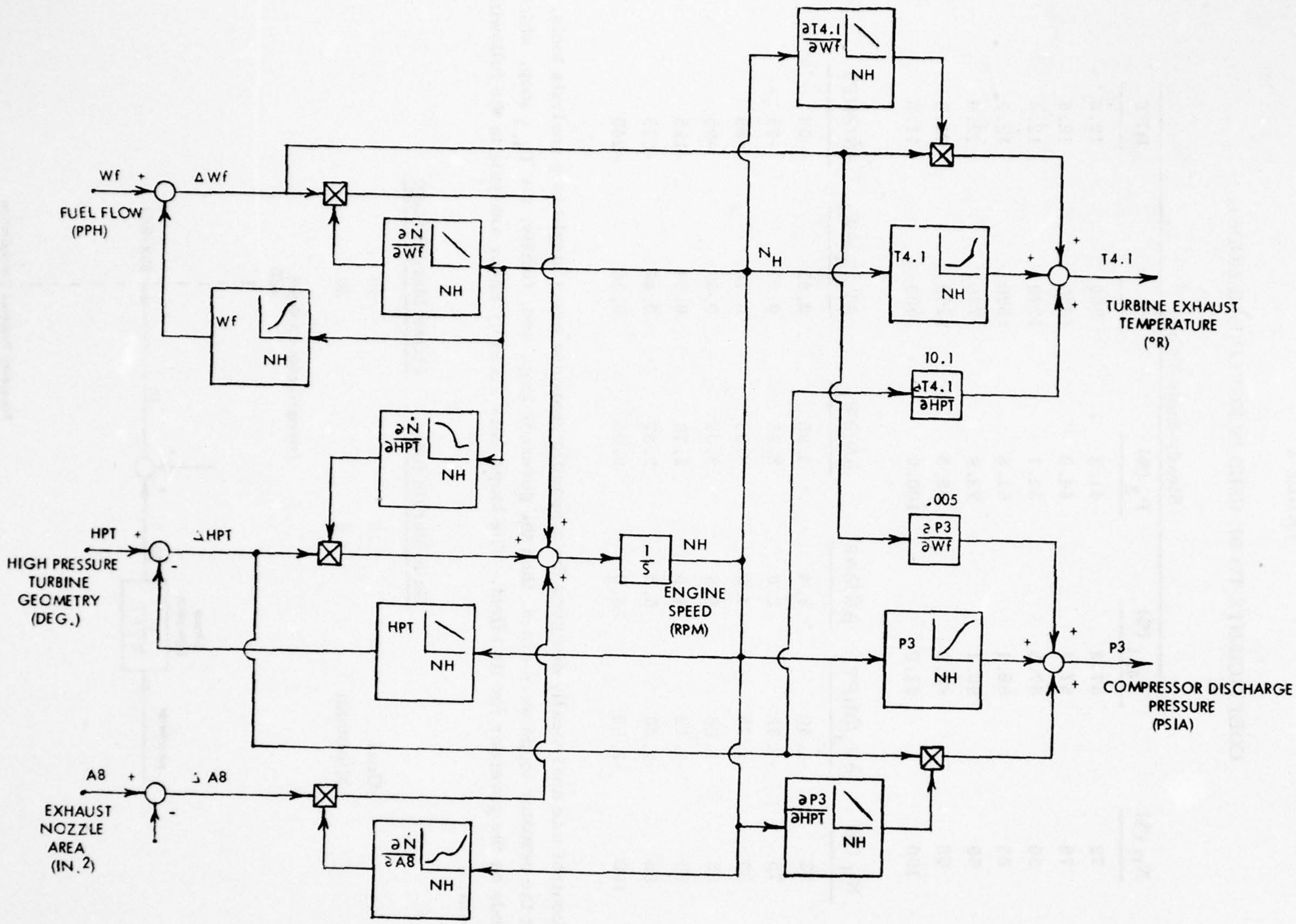

Figure 29. Nonlinear ATEGG Engine Model.

TABLE 2

COEFFICIENTS TO BE USED IN NONLINEAR MODEL

N_H (%)	Steady-State Values			
	$T_{4.1}$ (%)	P_3 (%)	W_f	HPT
72	57.3	41.2	950	12.8
75	57.4	44.8	1050	12.6
80	57.5	52.1	1270	12.4
85	58.1	61.8	1500	12.2
90	60.1	73.9	1775	12.0
95	60.8	88.5	2250	11.8
100	61.9	100.0	2800	11.5

N_H (%)	$\partial P_3/\partial HPT$	$\partial \dot{N}/\partial A8$	$\partial \dot{N}/\partial W_f$	$\partial T_{4.1}/\partial W_f$	$\partial \dot{N}/\partial HPT$
72	-1.40	2.4	3.85	0.83	-53
75	-1.52	2.6	3.65	0.78	-75
80	-1.75	4.2	3.33	0.70	-88
85	-1.96	5.6	3.02	0.62	-95
90	-2.18	4.6	2.70	0.54	-125
95	-2.40	5.4	2.37	0.46	-225
100	-2.63	14.0	2.05	0.38	-240

The control was analytically designed for a specific response using single loop analysis tools. First the actuator loops were sized, then the governor loop, and, finally, the $T_{4.1}$ loop, which depends on the governor for its effect. The loops were sized by linear analysis to the following criteria:

	Gain Margin (db)	Phase Margin (deg)
Goal	10	60
Minimum	6	30

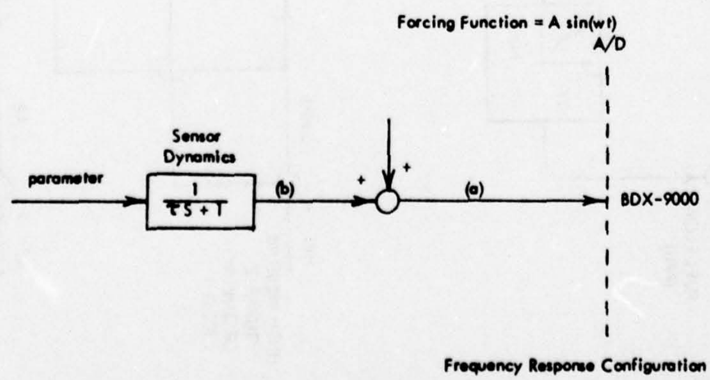

Figure 30. Frequency Response Input Summing.

Refer to Figure 31 for a typical speed loop plot. The following data show the values expected from linear analysis sizing and the values actually measured as a part of the Feasibility Test, which verified expected values:

Loop		Feasibility Test				Linear Sizing			
		Gain Margin (db at Hz)		Phase Margin (deg at Hz)		Gain Margin (db at Hz)		Phase Margin (deg at Hz)	
(60° PLA)	N	5.5 at	1.9	26 at	1.2	6 at	1.7	28 at	1.0
(72.7° PLA)	$T_{4.1}$	6	1.1	76	0.32	6	0.76	70	0.36
	W_{fA}	12	5.2	62	1.6	12	5.7	66	1.6
	W_{fB}	10	5.2			12	5.7	66	1.6
	HPT	12.5	2.4	30	0.9	11.6	2.75	38	1.2
	A8	8	7.8	52	3.4	10	8.5	56	3.2
	HPC_2	10	8	52	3.2	10	8.5	56	3.2

The stability margins given for the speed and temperature loops are at the worst operating conditions and were sized to the minimum margins.

Figures 32 and 33 demonstrate that the speed loop response does not change appreciably, whether the HPT is fixed or active at 60° PLA. The analytical and the expected results can be compared via Figures 31 and 33. Figures 34 through 36 show the closed loop response of speed and temperature to PLA input.

b. Ramp Tests

These transients were run according to the Feasibility Test Plan. In order to achieve the specified PLA ramp rate, the PLA rate limit was varied from its nominal 17.5°/sec to the required rate, and then a digital PLA command was used to step the system to the desired value. Multiple runs were made to get the required number of variables plotted.

Figure 37 shows a typical ramp response for conditions which will be run on ATEGG cyclic endurance testing.

Ramp and step transients showed good system performance in all cases. Normal accelerations in the operating region were made and no failures were detected for the specified parameter limits.

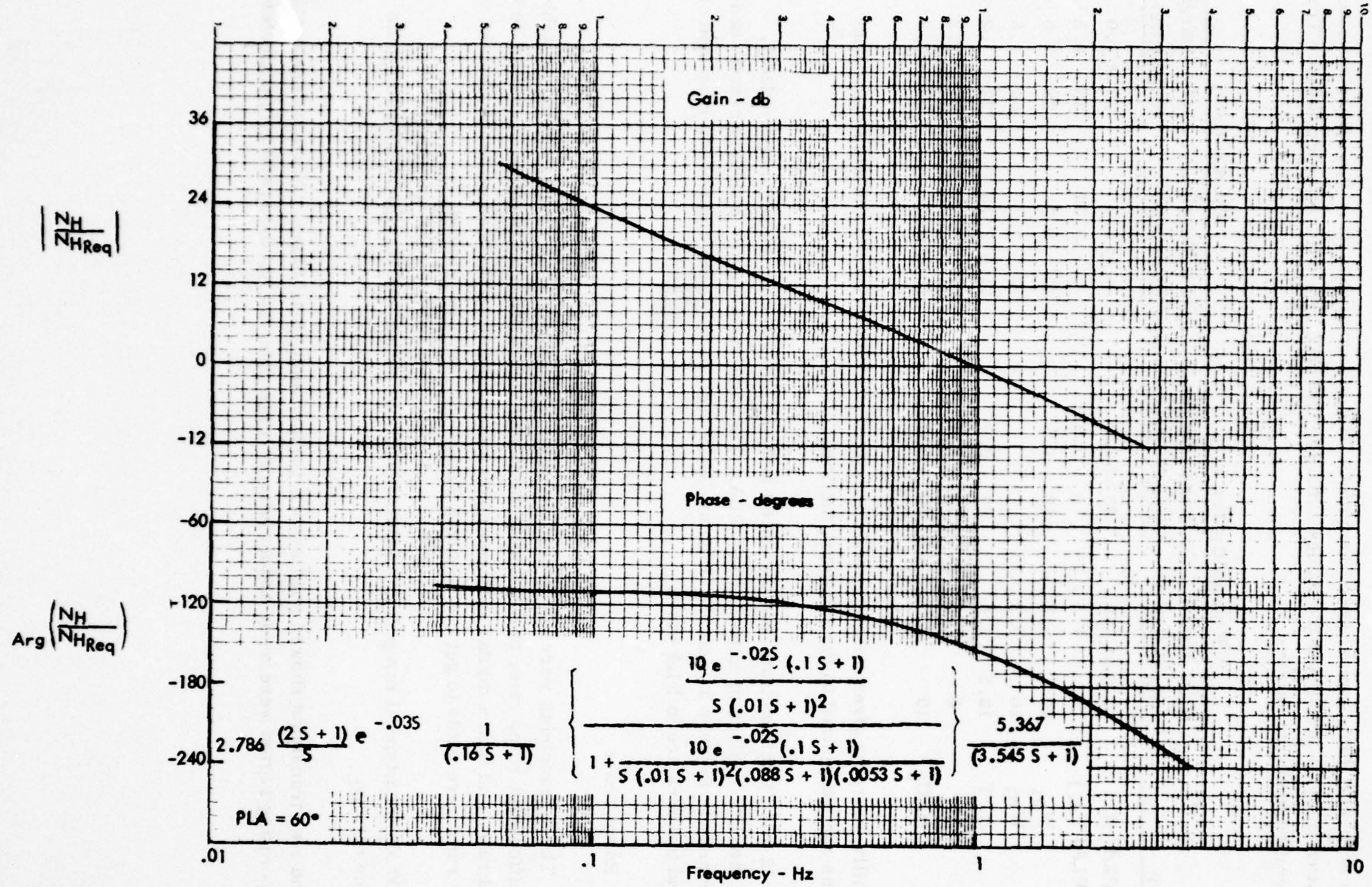

Figure 31. Calculated Speed Loop Response.

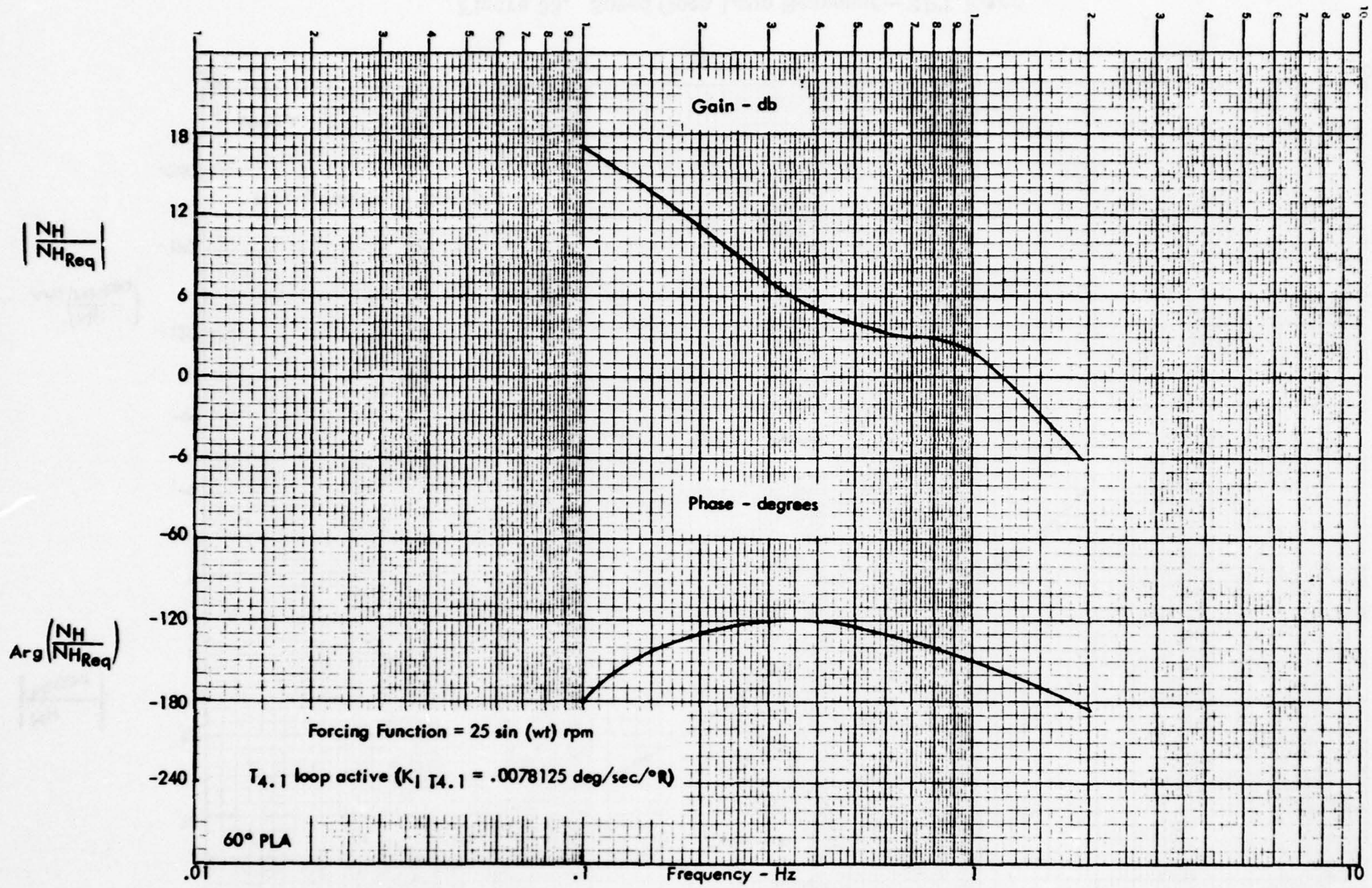

Figure 32. Speed Open Loop Response.

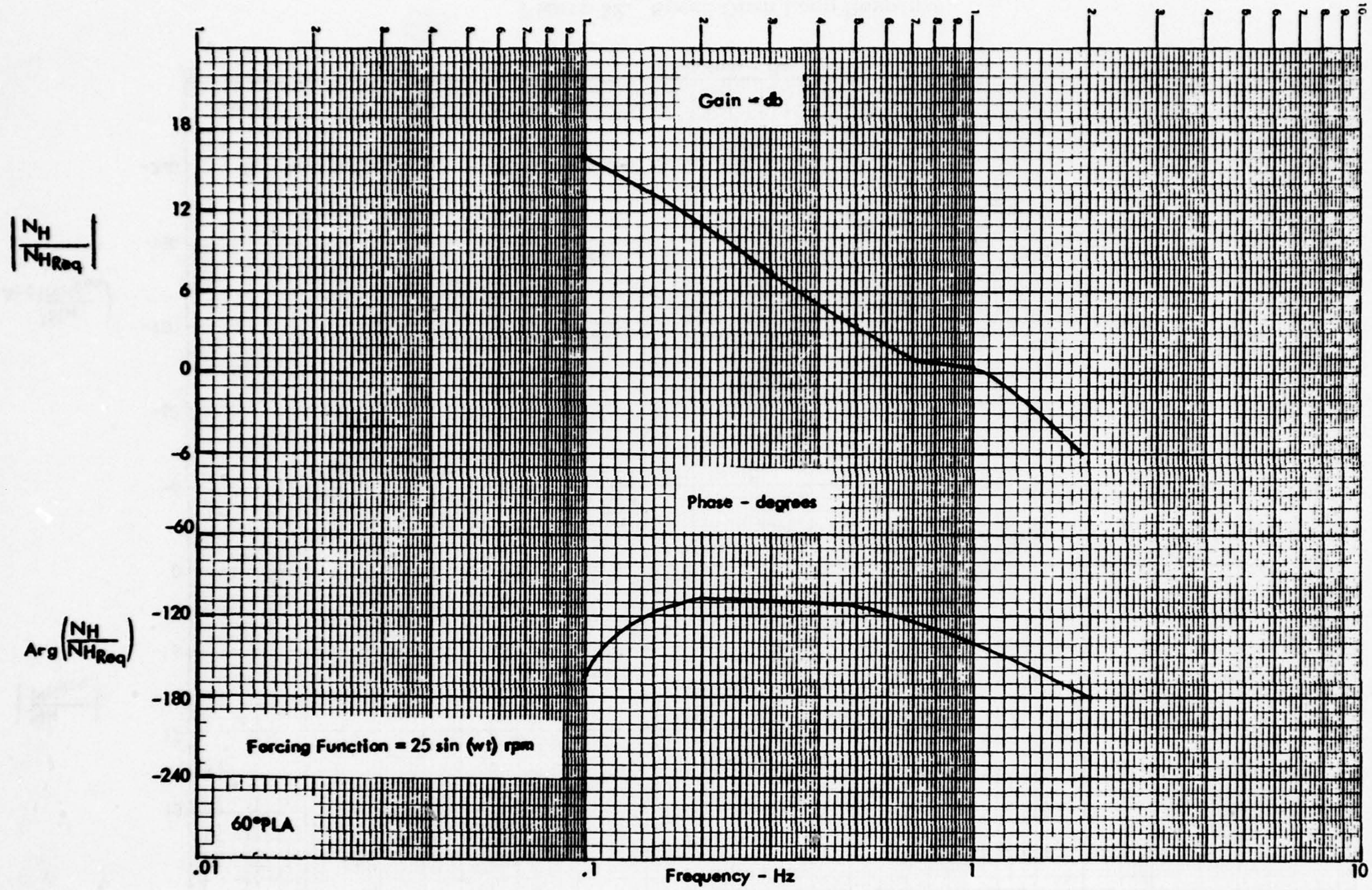

Figure 33. Speed Open Loop Response—HPT Fixed.

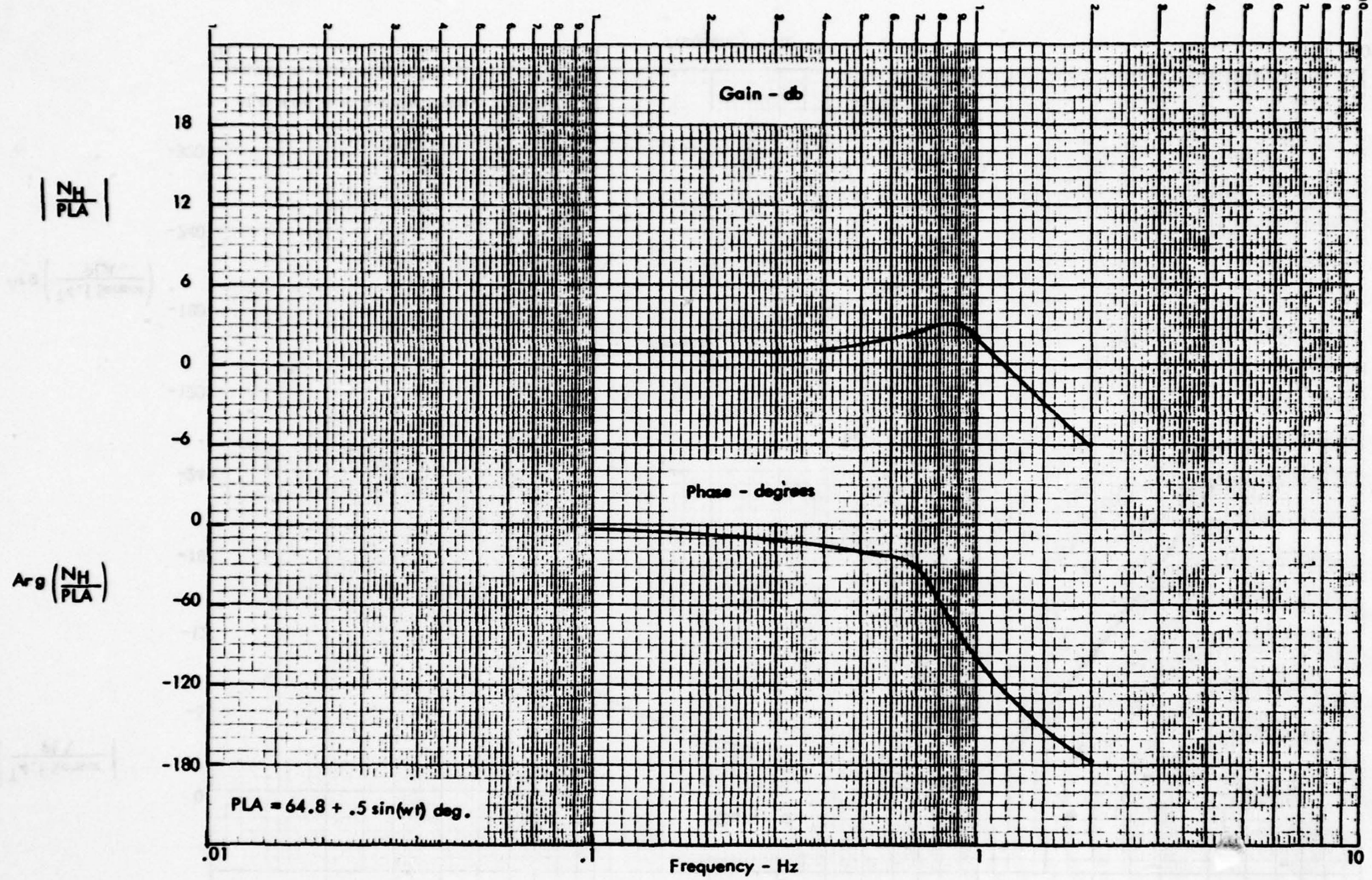

Figure 34. Closed Loop Response—PLA to Speed.

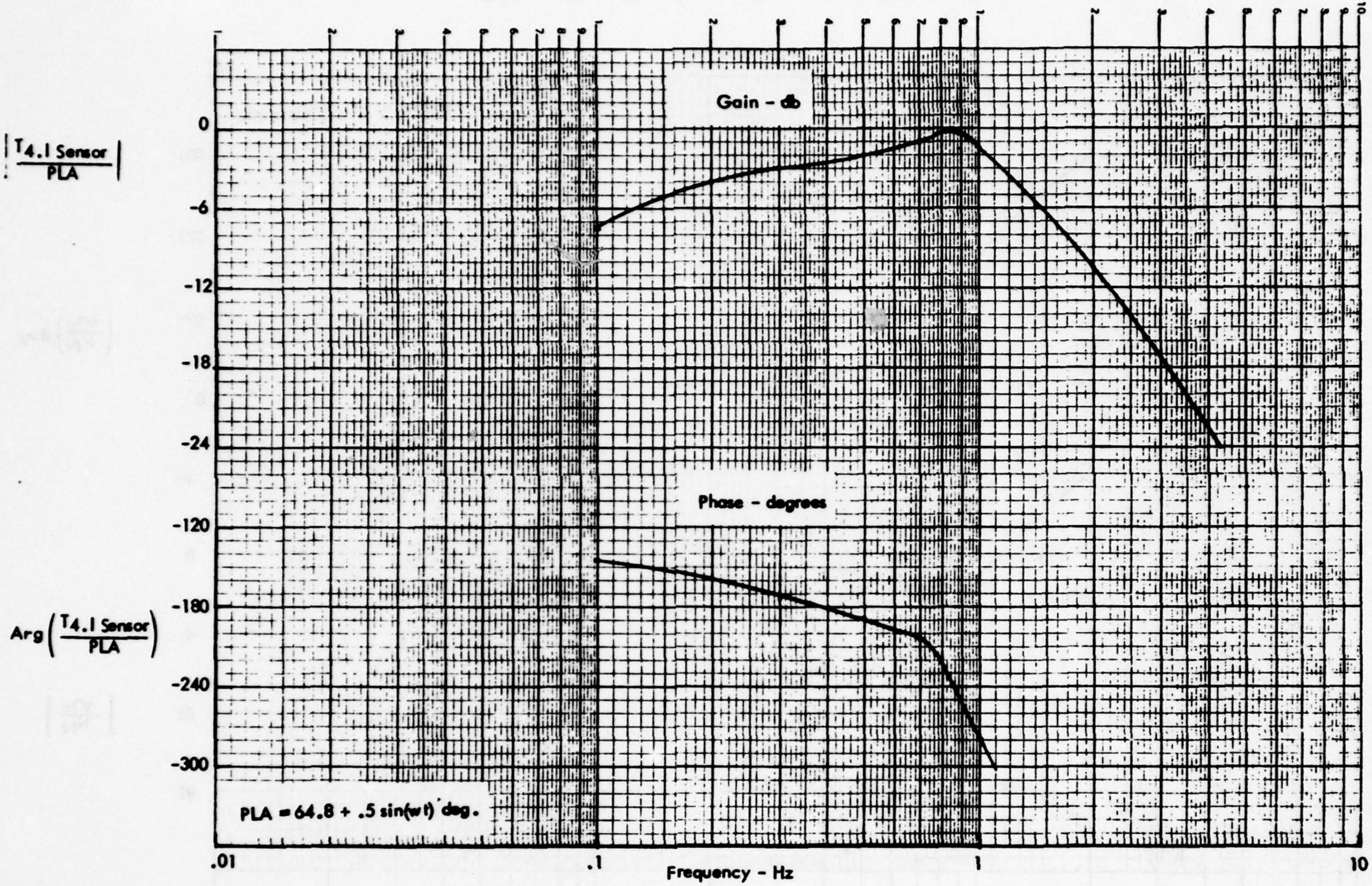

Figure 35. Closed Loop Response—PLA to $T_{4.1}$ Sensor.

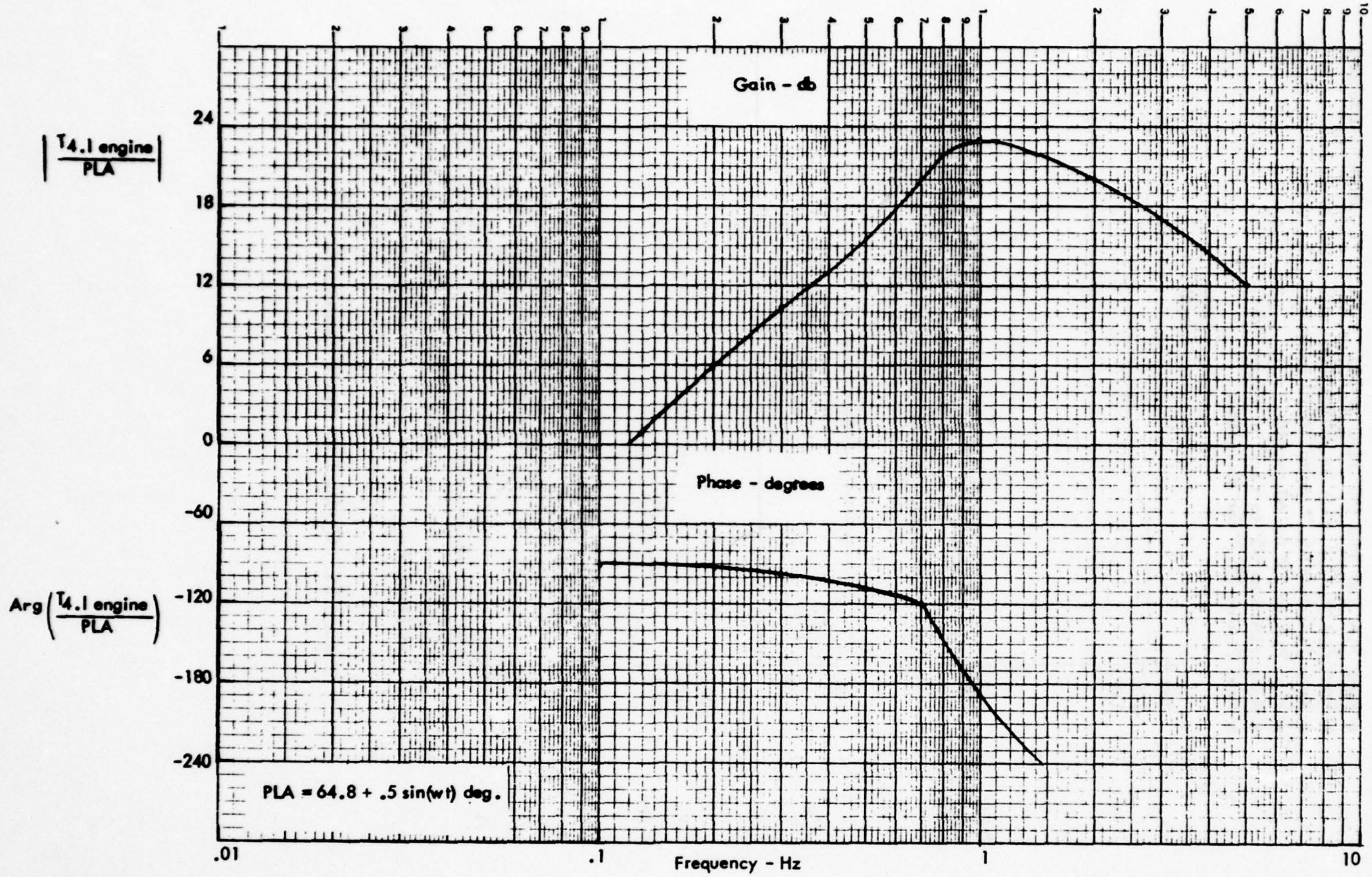

Figure 36. Closed Loop Response—PLA to Engine $T_{4.1}$.

- Ramp PLA from Idle (60° PLA) to 75.7° at a 1° PLA movement/second
- Hold PLA at 75.7° PLA for 30 seconds
- Ramp PLA from 75.7° to 95° in 20 seconds
- Hold PLA at 95° for 60 seconds
- Ramp PLA from 95° to 75.7° in 20 seconds
- Hold PLA at 75.7° for 30 seconds

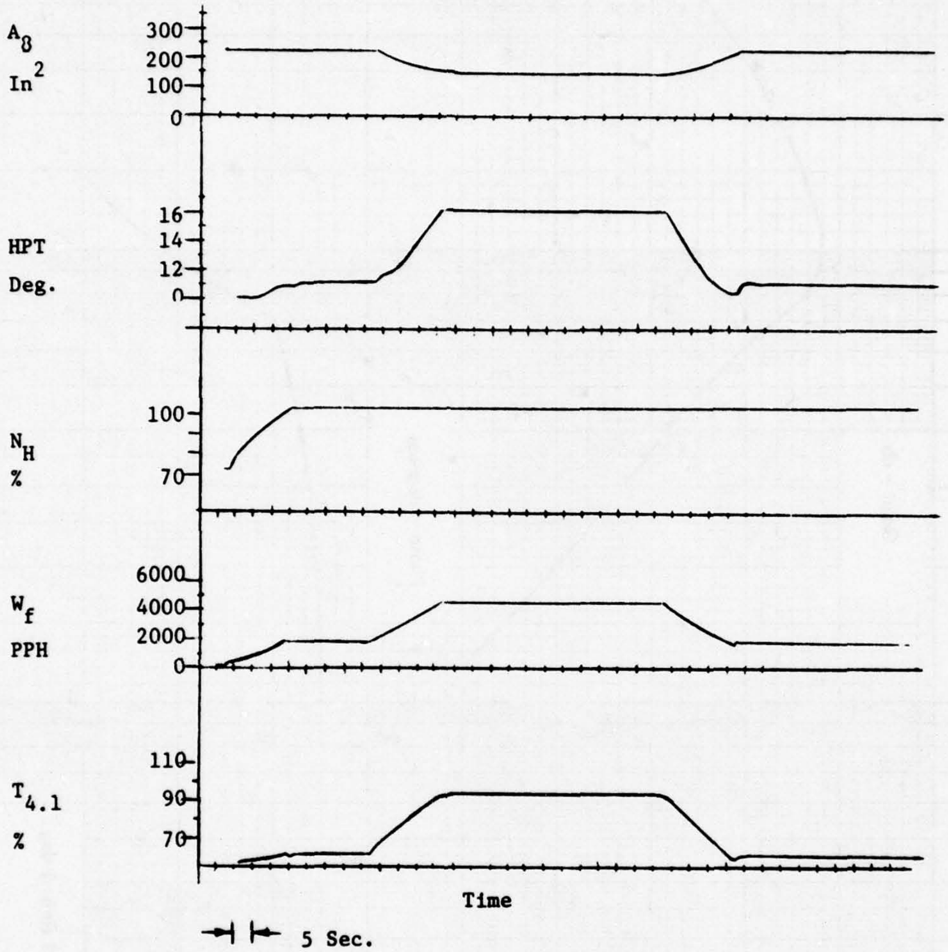

Figure 37. Cyclic Endurance Transient.

c. Steady-State Tests

Figure 38 shows the steady-state values of W_f and HPT versus PLA when running with the nonlinear model of Figure 29. To explain the results, it is necessary to look at the model functionally. Therefore:

$$
\begin{aligned}
\dot{\Delta} N_H &= (\partial \dot{N}/\partial W_f)\,\Delta W_f + (\partial \dot{N}/\partial HPT)\,\Delta HPT + (\partial \dot{N}/\partial A8)\,\Delta A8 \\
T_{4.1} &= (\partial T_{4.1}/\partial W_f)\,\Delta W_f + (\dot{\partial} T_{4.1}/\partial HPT)\,\Delta HPT + T_{4.1}\,[f\,(N_H)] \\
P_3 &= (\partial P_3/\partial W_f)\,\Delta W_f + (\partial P_3/\partial HPT)\,\Delta HPT + P_3\,[f\,(N_H)]
\end{aligned}
$$

where

$$
\begin{aligned}
\Delta W_f &= W_{f_{\text{Control Req}}} - W_f\,[f\,(N_H)] \\
\Delta HPT &= HPT_{\text{Control Req}} - HPT\,[f\,(N_H)] \\
\Delta A8 &= A8_{\text{Control Req}} - A8_{\text{Fix}}
\end{aligned}
$$

The results in Figure 38 were compared with data generated by running controlled transients with the ATEGG nonlinear digital simulation. That comparison showed the data in Figure 38 to be as much as 10% leaner in steady-state fuel flow required vs the numbers predicted through the digital nonlinear model for PLA settings up to 75°. Up to 75° PLA, each PLA setting indicates a unique N_H. This requires all Δ's to be zero in the preceding equations. Thus, the only way the model of Figure 29 can produce these different results is for the W_f $[f\,(N_H)]$ relationship to be incorrect. Closer examination of that schedule in Figure 29 showed that to be the case.

In the constant speed regime (above 75.7° PLA), the data of Figure 38 were up to 8% richer steady state than was anticipated through the nonlinear model. The discrepancy here was not unexpected. Fixed Δ's exist for any given PLA in the constant N_H region. The problem can be reduced to an equal number of knowns and unknowns if so desired by adjusting the partials. However, this was not the intention of using the nonlinear model. The values in Figure 38 are shown to indicate that no major problems exist with the model. The inability to match the steady-state data in the constant-speed range can be attributed to the simplicity of the model. For instance, the model does not account for changes in partials above 75.7° PLA.

The steady-state relationship of HPT in Figure 38 also differs from the steady-state relationship anticipated through the digital nonlinear model. Again in the variable-speed range this can be attributed to a scheduling mistake in the model of Figure 29, while in the constant-speed region the difference in the partials guarantees no match.

Figure 39 is a plot of two snap accels using the nonlinear model of Figure 29. When comparing with results from the digital nonlinear simulation, the model of Figure 29 was shown to be leaner than expected at speeds below 90%. This is due to incorrect N_H vs W_f schedule in that illustration. For the PLA step to 95°, the error between the two models grows during the portion

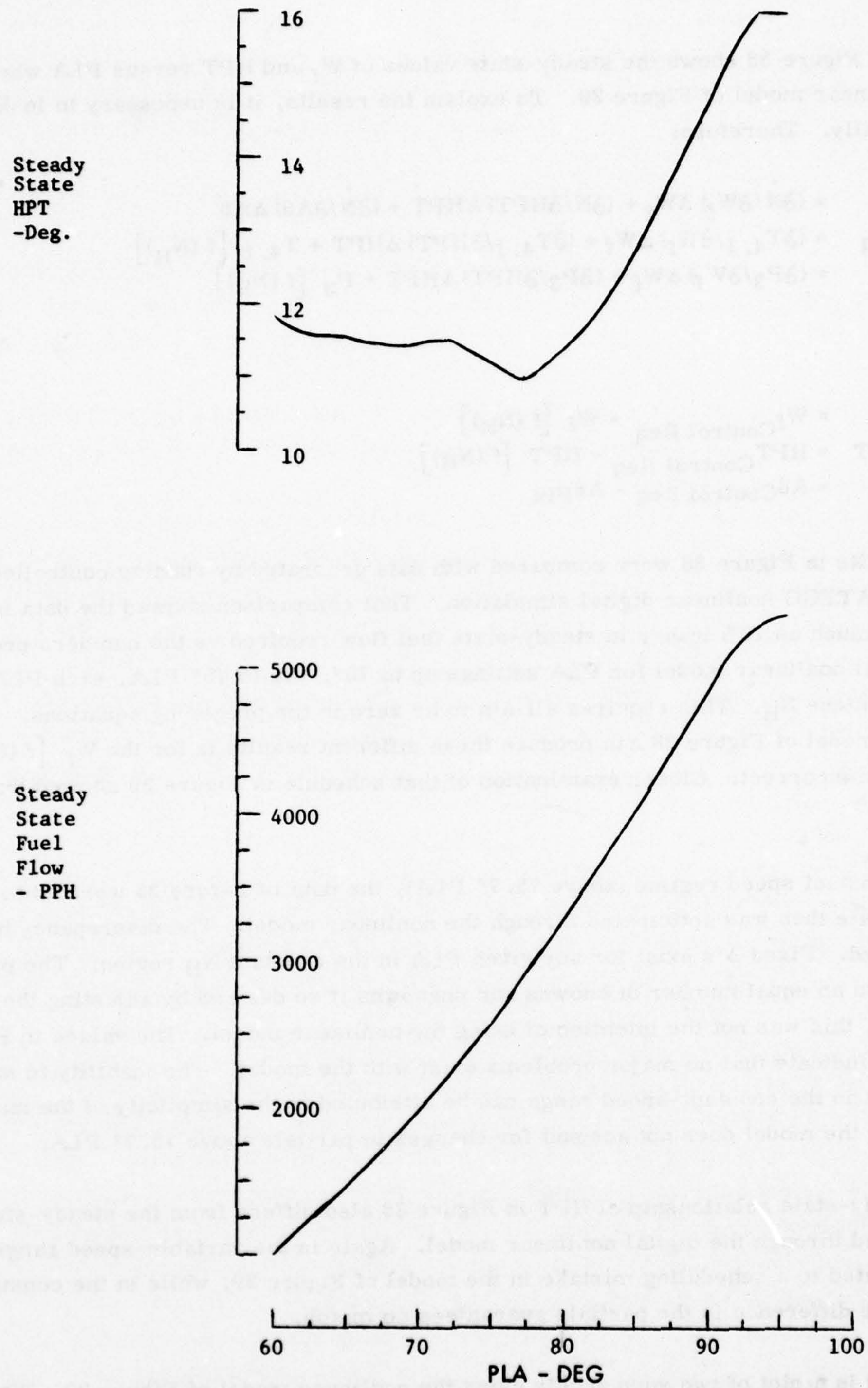

Figure 38. Steady-State W_f and HPT vs PLA.

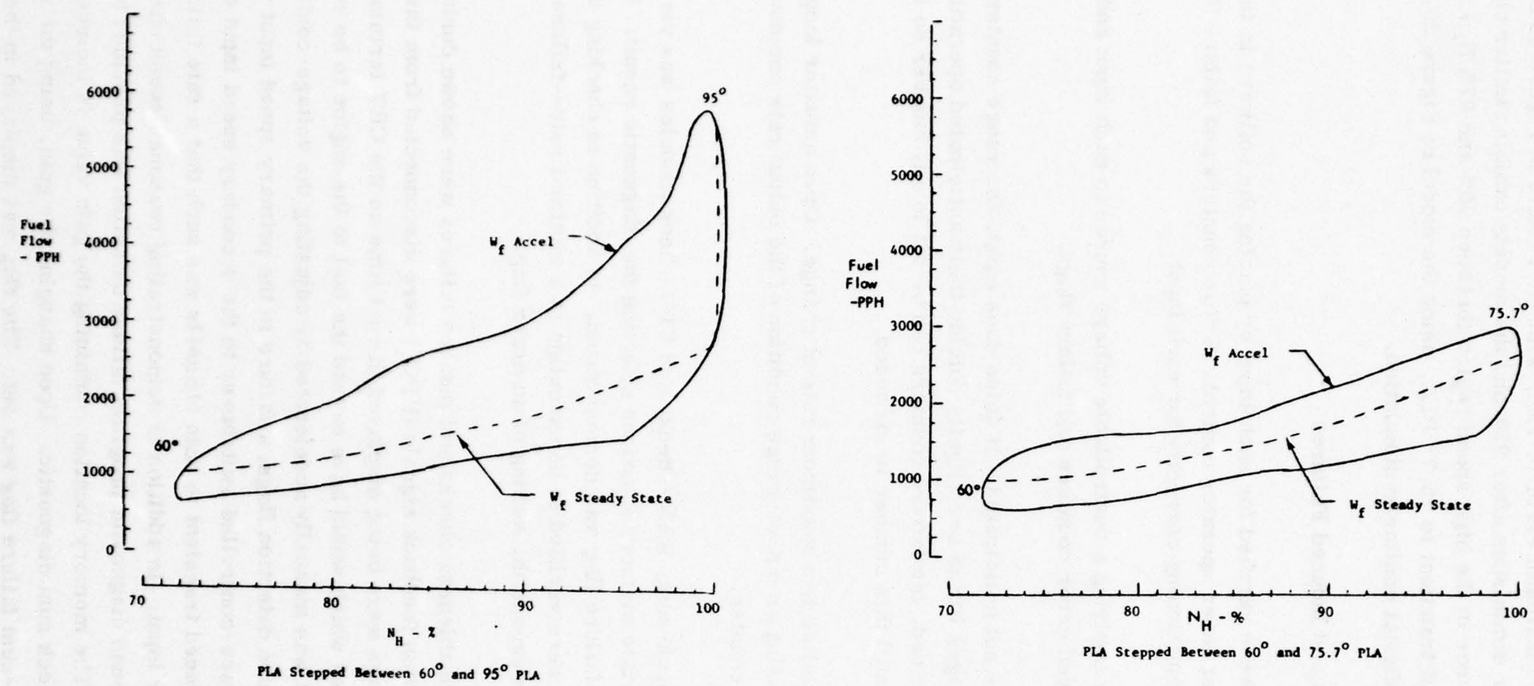

Figure 39. Cyclic Endurance Transient.

from 90% to 95% N_H, reaching a maximum error of 15%, with the results in Figure 39 being richer than expected. The error diminishes after 95% and the models exhibit similar characteristics up to 100% N_H. The error in the high speed region (between 90% and 97% N_H) is not considered serious. The stepped transient to 75.7° PLA, using the model of Figure 29, agrees favorably with results from the digital nonlinear simulation.

d. Reasonableness Checks and Induced Failures

Rate of change checks were verified for each input by placing the software in the test mode and ramping each input under operator control. Error counters and failure flags were displayed and determined to be functioning correctly for each input.

Range checks were exercised by applying a controllable voltage source to each input and verifying the operation of the displayed error counters and failure flags.

Excessive noise on the signals is not anticipated. If noise does exist, the range counters should still function correctly since ranges limits are slightly outside their anticipated operating limit. In case of rate limits being exceeded, the failure counters can be set to any number so that a rate failure will not be flagged until this number is exceeded.

Computed output requests are limited to a maximum rate of change. Open actuator loop detection logic was verified by causing an out-of-range condition of the output rate command and displaying the associated error counter.

The operation of the memory check-sum, RAM-check, and CPU-check modules was verified by changing the value of appropriate memory locations affecting the diagnostic result. In each case, the setting of the correct failure flag was demonstrated. In addition to checking the result of each test, the test programs were verified to be executing at a minimal rate—failure to maintain the proper rate of execution caused the setting of an error flag.

The following examples of reasonableness checks and induced failures were shown during the demonstration. Redundant position feedback signals (HPC_1) were disconnected from the engine model while failure detection flags were being displayed in real time on the CRT terminal: a range check failure was indicated which would have caused the fuel to the engine to be cut off. The simulated rotor speed input was manually accelerated by adjusting the voltage-controlled oscillator while monitoring failure detection flags: a failure in the primary speed input was indicated which effected a software-controlled switchover to the secondary speed input channel; the duration of the manually induced transient to both channels was such that a rate failure was also indicated for the secondary input. In addition to demonstrating reasonableness checks on inputs, an example of a background diagnostic program failure detection was provided by modifying a control program gain. The memory location containing the gain value is included in the memory area verified by the check sum diagnostic. Upon changing the gain, using the real-time interactive program, the check-sum failure flag was set. The flag was displayed in the system software flag register output on the BDX-9000 front panel lights.

e. Pulldown Tests

The limiter pulldown logic was tested and shown to be ineffective in achieving the desired parameter limit. For a P_3 overvalue causing a 1000 pph reduction from the governor fuel flow, only a net 100-pph reduction was effected at the engine as a result of the governor fighting the resulting speed drop by increasing fuel flow 900 pph. This 100-pph reduction would be even less with the $T_{4.1}$ loop closed.

The limiter does not work with the HPT loop active because when the limiter loop is active, the control trend in the HPT loop causes the HPT to open (see Figure 17). As it opens, its bias on the acceleration schedule causes $W_{f_{Fract}}$ to increase. Therefore, even if the integrator is frozen, as it is when on a limiter, and causes W_{f_I} to remain constant, W_{fP} is increasing (due to the speed error) and $W_{f_{Fract}}$ is increasing, thus canceling the effect of ΔW_f.

The present logic will work if the turbine is fixed. In the limiting case, $W_{f_{Fract}}$ will decrease due to speed decreasing, ΔW_f will decrease due to the limit being exceeded, and W_{fP} will increase slightly due to speed decreasing. In the overall, $W_{f_{Total}}$ will decrease. The amount it will decrease is basically dependent on K_L, the gain in the limiter loop, and K_P, the proportional gain in the governor loop. These gains have been sized through stability analysis. Thus, for any pulldowns during ATEGG BU 5 testing, this fixed turbine procedure will be used.

The remedy for limiting a parameter with the present method of limiting fuel flow with the HPT loop active can be achieved by making $W_{f_{Fract}}$ an output from a separate schedule and making this schedule independent of HPT. With this method, even with the HPT loop active, $W_{f_{Fract}}$ will always decrease in the limiting case, thus contributing to the decreasing effect of $W_{f_{Total}}$. The method will be verified before ATEGG BU 6.

SECTION VIII

CONCLUSIONS

The JTD Control Feasibility Study has yielded a controller which should satisfactorily accommodate anticipated ATEGG running. The control logic incorporated can maintain engine safety from surge, even during an expanded range of constant speed operation, with the addition of an HPT bias to the normal W_f/CDP acceleration schedule. Control of $T_{4.1}$ with HPT provides engine overtemperature protection. The use of 80% of the acceleration fuel flow as a component of the governor fuel flow provides for a limited authority integrator. Such an integrator has been shown to yield speed overshoots of less than 1%, which is considered acceptable.

Two analog engine models were developed for checkout of the control mode logic. A linear model was used for frequency response testing of both the fuel flow and the turbine control loops. A full-range nonlinear model was developed for examination of full-range excursions. Analog hardware limitations necessitated that an abbreviated full-range model be implemented. This model provided for adequate evaluation of those fuel flow and geometry control loops to be utilized during CY 77 and CY 78 ATEGG test activities.

Feasibility testing using these engine models and necessary interface models concluded that stable engine operation could be maintained with the fuel flow loop active and with or without a fixed turbine. The use of fuel flow alone to prevent an engine overtemperature condition proved to be unsatisfactory. This analog testing verified that analytical frequency response techniques were accurate. Thus, future control mode modifications, if simple enough, can be evaluated analytically and, consequently, minimize the need for analog testing.

Additional computer software evaluation during the feasibility testing showed the functions of timing and program control, input processing, output processing, fault monitoring and response logic, background diagnostics, and real time parameter monitoring to be operating properly.

SECTION IX

RECOMMENDATIONS

This Control Feasibility Study uncovered several areas requiring more thorough investigation for future ATEGG testing.

The present control mode involves closed-loop control of HPT and fuel flow only with the compressor airflow control fixed and the variable area exhaust nozzle scheduled on PLA. Since the actuator is presently being developed to vary the compressor geometry to accommodate different amounts of airflow for a given compressor speed, a method of controlling this actuator must be developed. In addition, a method of using A8 to control an engine parameter on a closed-loop basis should be further investigated.

The use of $\Delta P/P$ at the compressor discharge as a measure of engine airflow has suffered from lack of a ΔP sensor. In the event that sensor development does not progress significantly, an alternate means of generating an airflow signal should be examined. Further examination of the Rotor inlet temperature (RIT) synthesis routine presently programmed requires an accurate airflow representation. Thus, an alternate method of generating RIT should be investigated as well.

The method of pulling down $T_{4.1}$ or CDP by limiting fuel flow failed to execute as designed due to the fuel flow governor used. Thus, a means of coordinating geometry movement with fuel modulation in the case of an overtemperature or overpressure condition must be considered.

The start logic presently exists as an open-loop modulation of fuel flow with PLA up to the idle setting. Further necessary automation of the starting sequence will be explored based on the results of ATEGG BU 4 testing.

All of the aforementioned changes will be evaluated initially on the nonlinear digital simulation with improved actuator models based on updated engine test information. However, a real time evaluation should also be conducted on the Bendix hybrid computer. This would involve generating a hybrid model of ATEGG based on the digital nonlinear simulation.

APPENDIX A

JTD GAS GENERATOR CONTROL

INTERFACE HARDWARE SPECIFICATION

(Detroit Diesel Allison
Technical Data Report
No. AM. 1200-002)

TECHNICAL DATA REPORT

Detroit Diesel Allison, Division of General Motors Corporation, Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 1 OF	PAGES	REPORT NO AM.1200-002 C
TITLE JTD GAS GENERATOR CONTROL INTERFACE HARDWARE SPECIFICATION		PREPARED J. A. Weber		DATE 7-14-76
		CHECKED		
		APPROVED		

This document specifies the JTD gas generator (ATEGG) interface requirements. It has been prepared to document for Bendix ECD the requirements upon which preliminary Model EH-K1 electrical and mechanical design will be based.

1.0 Controller Outputs

This section defines outputs to the engine. The designation (A) indicates that the output is applicable to the gas generator. The designation (J) indicates that the output is applicable to the JTDE. JTDE information is preliminary and is included for planning purposes.

1.1 Gas Generator Fuel Flow Control (A) (J)

Two separate fuel valve actuator loops and logic channels will be used.

Torque Motor Drivers (one per fuel valve actuator loop)

Type: Pegasus Model 1103B servovalve

Resistance: 320 ohms/coil, 2 parallel coils

Inductance: 1.0 Henry/coil

Total Current: ±50 ma

Dither: 156 ±10% Hz, ±5 ma P-P

Relay Drivers (one per fuel valve actuator loop)

Switch: 115 V, 60 Hz power to a Double A Mod. QJ-06M-C-L-10A3 shutoff valve.

Position Feedback

Type: Schaevitz Model 100HR AC LVDT

Excitation-Demodulation: Daytronic Model 300D Transducer Amp - DC Output

Scaling: 2 lb/hr/mv DC, 7.5V DC = full flow = 15000 lb/hr

1.2 High Pressure Compressor Surge Avoidance Actuator - (HPC #2) (A) (J)

Slew Rate: 100% stroke/2 sec.

Torque Motor Driver

Type: MOOG Model 73-100 servovalve

Resistance: 200 ohm/coil, 2 parallel coils

Inductance: 1.0 Henry/coil

Total Current: ±15 ma. Minus milliamperes drives to 100% corrected speed.

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis, Indiana 46206	EDO NO. REF	PAGE 2 OF PAGES	REPORT NO. AM. 1200-002
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

Position Feedback (two per actuator)

Type: Linear potentiometers

Resistance: 5 K ohms

Excitation: 6.345 VDC

Scaling: 2.25 inch total stroke, center 2.0 inches used.
5.64 VDC = 100% NHC, 0.705 VDC = 70% NHC

1.3 High Pressure Compressor Air Flow Control Actuator (HPC #1) (A) (J)

Torque Motor Driver

Type: ABEX SB005

Characteristics: 5 GPM, 2 coil, 1000Ω/coil, 8.0 ma full scale, 24 ma max,
1.5 Hy/coil at 1000 Hz

Position Feedback

Type: 2, 5K pots

Scaling: TBD

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1.4 High Pressure Turbine Actuator (A) (J) -- Low Pressure Turbine Actuator (J)

Torque Motor Drivers (one per actuator)

Type: Servotronics Model 21-4

Rated Current: +500 ma, -200 ma. Negative ma command causes increased turbine area.

Resistance: 50 ohms/coil, 2 parallel coil

Inductance: .198 Henry/coil

Position Feedback - Resolver (one per actuator) (Bendix system) (J)

Primary Voltage: 7.0 V RMS @ 1450 Hz

Secondary Voltage: 3.5 ±3% V RMS @ 1450 Hz

Impedance, ZRO (Min.): 95 + J 568, 576/ 80.5°

Electrical Error (Max.) @ 77°F: ±7 minutes

Phase Shift: 5° leading (estimated)

Wiring: Six wires with internal shorted rotor compensating winding

FORM 4936 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis, Indiana 46206 TITLE	EDO NO. REF.	PAGE 2a OF PAGES PREPARED CHECKED APPROVED	REPORT NO AM.1200-002 DATE

Position Feedback - Potentiometer (A) (two per actuator)

Type: Linear Potentiometer

Resistance: 2K ohms

Excitation: 6.345 VDC

Scaling: .5 inch stroke, use 16.3% to 57% position.

57% point on pot =38.8 sq. in. turbine area = 9.25° engine simulation

16.3% point on pot = 53.8 sq. in. turbine area = 16.4° engine simulation

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FORM 4936 (REV. 11-71)

1.5 Primary Nozzle Actuator - (A8)

1.5.1 Primary Nozzle Actuator (A)

Slew Rate - 100% stroke/0.5 sec.

Torque Motor Driver

Type: Denison servovalve

Total Current: ±8 ma. Negative ma command causes decreased area.

Resistance: 1,000 coil, 2 parallel coils

Inductance: 1.5 Henry/coil @ 1000 Hz

Position Feedback (two per actuator)

Type: Linear potentiometers

Resistance: 5K ohms

Excitation: 6.345 VDC

Scaling: 6 inch stroke, rigged 30-83% travel.
1.90 V = 103 $in.^2$, 5.20 V = 230 $in.^2$

1.5.2 Primary Nozzle Actuator (J)

DISTRIBUTION:

Torque Motor Driver

Type: ABEX SB025

Characteristics: 25 GPM, 2 coil, 1000Ω/coil, 8.0 ma full scale, 24 ma max,
1.5 Hy/coil @ 1000 Hz

Position Feedback (two per actuator)

Type: 2, 5K linear potentiometers

Excitation: 6.345 VDC

Scaling: TBD

2.0 Controller Inputs

This section defines engine parameters sensed by the controller. (A) indicates that the parameter is applicable to the gas generator. The designation (J) indicates that the parameter is applicable to the JTDE. JTDE information is preliminary and is included for planning purposes.

FORM 4936 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison, Division of General Motors Corporation, Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 4 OF PAGES	REPORT NO. AM.1200-002
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

2.1 High Pressure Rotor Speed (A) (J)

Two sensors are used for redundancy

Sensor Type: Berkley Model 466-120 Tachometers

Input Sensing Circuit Impedance: 10K ohms min.

Input Amplitude: 200 mv RMS to 20 V RMS

Signal Characteristics: Distorted sine wave (strong third harmonics)

Common Mode Rejection: 54 db at low level

Accuracy: ±0.2% of pt (conditioning circuit channel accuracy)

Frequency:

100% speed - 9348.4 Hz

Min. speed - 934.84 Hz (10%)

Max. speed - 9815.82 Hz (105%)

2.2 Low Pressure Rotor Speed (J)

Two sensors are used for redundancy

Sensor Type: Electro Model 3015 HTB

Inductance: 31 milliHenries max.

DC Resistance: 110 ohms max.

Signal Level:

1V peak to peak min.

14V peak to peak max.

Input Impedance: 100K ohms min.

Common Mode Rejection. 54 db at low level

Accuracy: ±0.2% of pt at low level

Frequency:

100% Speed - 34,219.13 Hz

Min. Speed - 3,421.913 Hz (10%)

Max. Speed - 35,930.908 Hz (105%)

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FORM 4536 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 5 OF PAGES	REPORT NO. AM1200-002
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

2.3 Pressures

Engine Inlet, PT1 (A) (J)

Range: 0.5 to 50 psia

Accuracy: .05% F.S.

Response: 14 msec read time

Fan Discharge Mach Number (J)

[(PT - PS)/PT] 13

PT 13

Range: 2 to 76 psia

Accuracy: .05% F.S.

Response: 14 msec read time

(PT-PS) 13

Range: 0.1 to 20 psid

@ 2 to 76 psia

Accuracy: .05% F.S.

Response: 14 msec read time

Compressor Inlet PT2.1 (J)

(Note: PT13 and PT2.1 may be sensed by only one sensor in final control definition)

Range: 2 to 76 psia

Accuracy: .05% F.S.

Response: 14 msec read time

Compressor Discharge Mach Number (A) (J)

(PT-PS)/PT 2 - ATEGG

(PT-PS)/PT 3 - JTD

PT2 and PT3

Range: 10 to 300 psia

Accuracy: .05% F.S.

Response: 14 msec read time

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FORM 4316 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis Indiana 46206	EDO NO. REF.	PAGE 6 OF PAGES	REPORT NO AM.1200-002
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

PS2 and PS3

Range: 10 to 300 psia

Accuracy: .05% F.S.

Response: 14 msec read time

High Pressure Turbine Discharge, (A) (J)

PT4.1 - JTD

PT4 - ATEGG

Range: 10 to 125 psia

Accuracy: .05% F.S.

Response: 14 msec read time

Tail Pipe (J)

PT7 - JTD

Range: 2 to 90 psia

Accuracy: .05% F.S.

Response: 14 msec read time

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2.4 Temperatures

Engine Inlet, T1 (A) (J)

Type: Chromel/Alumel Thermocouple

Number Inputs: 2 clusters interconnected - 1 channel

Range: 320°R to 800°R

Accuracy: ±9°R

Compressor Inlet, T2.1 (J)

Type: Chromel/Alumel Thermocouple

Number Inputs: 2 clusters

Range: 349°R to 990°R

Accuracy: ±9°R

FORM 9536 (REV. 11-71)

High Pressure Turbine Exit (A) (J)

T4 - ATEGG

T4.1 - JTD

Type: Thoriated Platinum/Platinum - 40% Rhodium Thermocouple

Number Inputs: One Channel

Range: To be specified.

EMF Output vs Temperature:

Table 1 - Pt ($ThO2$)/PT - 40% Rh

Table 2 - Nichrome vs Engelhard Alloy 9R682 (Extension Lead wires for Pt (ThO^2) vs Pt - 40% Rh thermocouple)

Accuracy: ±9°R

Compressor Discharge, T2 (A), T3 (J)

Type: Chromel/Alumel Thermocouple

Number Inputs: One channel

Range: 320°R to 1750°R

Accuracy: ±9°R

Turbine Blade Metal,Pyrometer (A) (J)

Type: Solar optical pyrometer

Output: Variable voltage

Frequency = 70. turbine blades x high pressure compressor speed

Voltage level = optical pyrometer output per Table 3

Range: 1700°R to 2300°R

Temperatures Measured:

Peak blade temperatures

Average blade temperatures

(All of these temperature measurements may not be required in final control definition)

Accuracy: ±.1% F.S.

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TECHNICAL DATA REPORT

Detroit Diesel Allison, Division of General Motors Corporation, Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 8 OF PAGES	REPORT NO. AM.1200-002

TITLE

Table 1. EMF Vs. Temperature Relationship
Thoriated Pt (Lot 1B 05774529) Vs. Pt-40% Rh (Bar Z)

PREPARED | DATE
CHECKED
APPROVED

IPTS 68

EMF Millivolts | Temperature °C | Reference Junction 0°C

Temperature	EMF
-50	-.212
-40	-.175
-30	-.136
-20	-.092
-10	-.046
0	0
+25	+.148
50	.293
75	.467
100	.651
150	1.064
200	1.521
250	2.019
300	2.551
350	3.117
400	3.713
500	4.980
600	6.366
700	7.859
800	9.464
900	11.169
1000	12.984
1100	14.894
1200	16.883
1300	18.951
1400	21.086
1500	23.236
1600	25.394
1650	26.473

Notes:

1. Data obtained from tests 4022, 4023 and 4026.
2. Thoriated Pt thermoelement (.040" diameter) was annealed at 1400°C for 15 minutes prior to testing. Pt-40% Rh thermoelement (.040" diameter) was annealed at 1600°C for 15 minutes prior to testing.
3. Annealing and Testing was performed in air.

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FORM 4936 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison, Division of General Motors Corporation, Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 9	PAGES OF	REPORT NO. AM.1200-002

TITLE

Table 2. EMF Vs. Temperature

PREPARED | DATE

CHECKED

APPROVED

Nichrome vs. Engelhard Alloy 9R682 (Extension Lead Wires for Pt (ThO_2) vs. Pt-40% Rh Thermocouple)

Temperature (°C)	EMF (mv.)
-50	-.140
-40	-.108
-30	-.077
-20	-.047
-10	-.024
0	0
+25	+.077
50	.174
75	.323
100	.496
150	.946
200	1.482
250	2.052
300	2.598
350	3.137
400	3.703
500	4.925
600	6.267
700	7.746
800	9.349
900	11.077
1000	12.910

DISTRIBUTION

FORM 4936 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 10 OF PAGES	REPORT NO. AM.1200-002
TITLE Table 3. Calibration of Analog and Digital Readout Subsystem		PREPARED CHECKED APPROVED	DATE

Calibration Temperature (Expected Reading)	Calibration Voltage (mV)	Calibration Temperature (Expected Reading)	Calibration Voltage (mV)
1300	46.49	1760	1072.29
1320	54.36	1780	1195.31
1340	64.56	1800	1329.96
1360	75.76	1820	1477.13
1380	88.64	1840	1637.75
1400	103.42	1860	1812.83
1420	120.34	1880	2003.45
1440	139.63	1900	2210.77
1460	161.59	1920	2436.05
1480	186.49	1940	2680.64
1500	214.65	1960	2946.03
1520	246.44	1980	3233.82
1540	282.20	2000	3545.77
1560	322.34	2020	3883.82
1580	367.27	2040	4250.10
1600	417.46	2060	4646.97
1620	473.37	2080	5077.03
1640	535.52	2100	5543.18
1660	604.46	2120	6048.66
1680	680.75	2140	6597.07
1700	765.01	2160	7192.47
1720	857.89	2180	7839.41
1740	960.07	2200	8543.01

DISTRIBUTION

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 10a OF PAGES	REPORT NO AM.1200-002
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

2.5 Power Lever Angle

Type: Potentiometer

Excitation: 6.345 VDC

Scaling: 0-6.345V equivalent to 0-95° PLA

Engine idle = 60° PLA

2.6 EHKI Fault Indicator Discrete

Logic Level: 28V when no fault
0V when EHKI detects fault condition requiring shutdown

Current Drive Capability: 800 ma max.

2.7 Fuel Cut-off Discrete

Logic Level: 28V when fuel is to be enabled
0V when fuel is to be cut off

Current Drive Capability: 800 ma max

DISTRIBUTION

TECHNICAL DATA REPORT

Detroit Diesel Allison, Division of General Motors Corporation, Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 11 OF PAGES	REPORT NO AM.1200-002
TITLE		PREPARED / DATE	
		CHECKED	
		APPROVED	

3.0 Controller Environment

3.1 Vibration

The controller shall be subjected to a vibration test in accordance with MIL-STD-810, Method 514.2. Tests shall be conducted in accordance with Procedure I for equipment Category b.1 (Table 514.2-II) curves "F" and "L" (figure 514.2-2).

3.2 Temperature

The controller shall be designed to withstand an environment of 300°F for eight hours. The controller will be supplied with fuel at 75°F, 20 psig at this time.

The controller shall also be designed to operate in free air at 110°F with no cooling fuel supplied.

4.0 Input Power

The controller will be supplied 32-40 volts DC. No more than 10 amperes shall be required.

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5.0 EMC

The controller shall be designed to be capable of meeting the requirements of the latest issue of MIL-STD-461.

The controller, auxiliary memory, and test equipment shall be compatible with the engine test set up.

6.0 Processor Requirements

The controller shall incorporate a stored program, general purpose digital computer. The word length shall be 16 bits minimum. It shall be capable of addressing at least 16,384 16 bit words of memory.

The instruction repertoire shall be as described in the Bendix Programming Manual, Document # TBD.

A non volatile, electrically reprogrammable memory shall be provided. This memory does not have to be contained within the mechanical outline.

FORM 4526 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 12 OF PAGES	REPORT NO. AM.1200-002
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

The computer shall interface with computer support equipment that makes it possible to load and verify memory and troubleshoot hardware or software problems.

The computer shall incorporate hardware alarms to detect loss of program control and malfunctions in the timing system.

7.0 Package

The package shall conform to the mounting configuration and outline as shown in Bendix drawing FXR-247029, vibration mockup.

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FORM 4536 (REV. 11-71)

APPENDIX B

JTD GAS GENERATOR CONTROL

SOFTWARE SPECIFICATION

(Detroit Diesel Allison
Technical Data Report
No. AM. 1200-001)

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 1 OF PAGES	REPORT NO. AM.1200-001 A
TITLE JTD GAS GENERATOR CONTROL SOFTWARE SPECIFICATION		PREPARED J. A. Weber, Jaubh CHECKED APPROVED	DATE 7-14-76

This document specifies the JTD gas generator (ATEGG) control software requirements. It has been prepared to document for Bendix ECD the requirements upon which will be based the software prepared for the Model EH-K1 control feasibility test.

1. Data Checks

This section describes the tests performed on input data before it is used in output computation and on output parameters before being applied to the engine.

1.1 Input Data

1.1.1 Range

Range checks shall be performed on input data per Table 1.1-1

Table 1.1-1 Input Data Range

Parameter	Range
HP rotor speed (2 channels)	0 - 10,000 Hz
LP rotor speed (2 channels)	NA, gas generator
Engine inlet pressure (PT1)	.5 - 50 psia
Fan discharge Mach number	NA, gas generator
Compressor inlet pressure	NA, gas generator
Compressor discharge total pressure	10 - 300 psia
Compressor discharge static pressure	10 - 300 psia
HP turbine discharge pressure	10 - 125 psia
Tail pipe pressure	NA, gas generator
Engine inlet temperature	420 to 800°R
Compressor inlet temperature	NA, gas generator
HP turbine exit temperature	To be specified.
Tail pipe temperature	NA, gas generator
HP turbine blade temperature	1700 to 2300°R
Fuel valve position (2 channels)	0 to 10000 lb/hr
HP compressor surge avoidance	0 to 2 in.
HP compressor flow	80 to 120
HP turbine position	9 to 17

DISTRIBUTION:

FORM 4936 (REV. 11-71)

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TECHNICAL DATA REPORT

Detroit Diesel Allison, Division of General Motors Corporation, Indianapolis, Indiana 46206	EDO NO. REF	PAGE 2 OF PAGES	REPORT NO. AM.1200-001 A
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

Table 1.1-1 (con't)

Parameter	Range
LP turbine position	NA, gas generator
PLA	0 to 100 degrees
Primary nozzle position	100 to 230 sq.in.
Compressor outlet temperature	420 to 1750 degrees R
Secondary nozzle position	NA, gas generator

Table 1.1-2 Maximum Rate of Change (20 msec)

Parameter	+ limit	- limit
HP rotor speed (2 channels)	0.45%	0.45%
LP rotor speed (2 channels)	NA, gas generator	
Engine inlet pressure	1 psia	1 psia
Fan discharge total pressure	NA, gas generator	
Fan discharge pressure differential	NA, gas generator	
Compressor discharge total pressure	4 psia	4 psia
Compressor discharge static pressure	4 psia	4 psia
HP turbine discharge pressure	1 psia	1 psia
Tail pipe pressure	NA, gas generator	
Engine inlet temperature	1°R	1°R
Compressor inlet temperature	NA, gas generator	
HP turbine exit temperature	20°R	20°R
Tail pipe temperature	NA, gas generator	
HP turbine blade temperature	5°R	5°R
Fuel valve position (2 channels)	400 lbs/hr	400 lbs/hr
HP compressor surge avoidance	0.1 in.	0.1 in.
HP compressor flow	0.8	0.8
HP turbine position	.06	.06
LP turbine position	NA, gas generator	
PLA	2°	2°
Primary nozzle position	1.50 sq.in.	1.5 sq. in.
Secondary nozzle position	NA, gas generator	
Compressor outlet temperature	10°R	10°R

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FORM 4956 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 3 OF PAGES	REPORT NO AM.1200-001A
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

1.1.2 Rate of change

After performing the range checks on input data specified in 1.1.1 perform rate of change tests specified in Table 1.1-2. The maximum change is based on 20 millisecond sample rates on all parameters.

1.2 Output data

After calculation of output data perform a reasonableness test based upon maximum rate of change as specified in Table 1.2. The maximum change is based upon a 20 millisecond update rate on all outputs. No range checks are made as it is assumed that output scaling uses the full, available range.

Table 1.2 Output Data Maximum Change

Output	+ Change	- Change
Primary fuel command	400 lbs/hr	400 lbs/hr
Secondary fuel command	400 lbs/hr	400 lbs/hr
HP compressor surge avoidance	0.1 in.	0.1 in.
HP compressor flow	0.8	0.8
HP turbine area	0.06	0.06
LP turbine position	NA, gas generator	
Primary nozzle position	1.50 sq.in.	1.50 sq.in.
Secondary nozzle position	NA, gas generator	

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1.3 Error counters

A counter shall be made maintained for each data check channel - range and rate of change. Each time an error condition is detected the counter shall be incremented. If the error condition is not present in the next program interval, the counter shall be zeroed.

The number at which an error flag is set shall be variable by a memory location change. Each channel shall be individually controlled.

When the preset number is reached, the program shall exit to the failure routine.

FORM 4356 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 4 OF PAGES	REPORT NO. AM.1200-001 A
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

2.0 Self test

2.1 CPU

The software shall include a central processor self test routine that exercises all instructions in the repertoire. The arguments used in this test shall be representative of data used in the control program. A failure of the CPU self test shall cause an exit to the fail routine. The CPU self test shall be executed at least ten times per second.

2.2 Memory

The program shall incorporate a memory sum check on all portions of the memory not committed to data, i.e. program and constants. The sum check shall be executed at least ten times per second. Failure shall cause an exit to the fail routine.

2.3 Input/Output

The program shall check the position of each output device as measured by the A/D converter against the computed output value. This check shall be performed each computation loop time. Failure shall cause an exit to the fail routine.

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3.0 Failure routine

3.1 Output conditions

Upon entry to the failure routine all outputs shall be zeroed. This will cause to be shutoff, the turbine to be fixed; and the nozzle to be slewed to an open position.

3.2 Failure indications

Positive indication of a failure condition shall be made via the operating equipment.

3.3 Failure diagnosis

The fail routine shall set non-volatile flags that indicate which failure condition - data checks, output checks, or self test - caused the exit to the failure routine. These flags shall be sufficient to indicate which particular test, for example, NH range test, memory sum check, fuel valve feedback, etc caused the exit to the failure routine.

These flags shall be accessible via the computer operating equipment.

FORM 4536 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison, Division of General Motors Corporation, Indianapolis, Indiana 46206	EDO NO. REF.	PAGE 5 OF PAGES	REPORT NO. AM.1200-001 A
TITLE		PREPARED / DATE	
		CHECKED	
		APPROVED	

4.0 Control logic

Control logic shall be mechanized. Ref. TDR AM.1200-003.

5.0 Operational test requirements

5.1 Pulldown tests

All limiters shall have selectable, lower valve limits (pulldown tests). These pulldowns shall be individually selectable via the operating equipment. Pull down limits are listed in Table 5.1.

Table 5.1

Parameter	Limit	Pulldown limit
HP rotor speed	105%	85%
Compressor discharge total pressure	275 psia	60 psia
Rotor outlet temperature	TO BE	SPECIFIED
HP turbine blade temperature, peak	2300°R	1500°R

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5.2 Actuation tests

Upon command from the computer operating equipment it shall be possible to slew each actuation system and the fuel valves to the extremes of their travel. This test shall be interlocked with the fuel shutoff discrete so that the test cannot be performed while the gas generator is running. An indication of pass/failure shall be provided.

6.0 Operator/software interface

6.1 Mode control

No mode inputs to the program shall result in its performing control per section 4.0. In order to accomplish the tests performed in section 5.0 it must be possible to command subtests via the operating equipment. These subtests shall include the following pulldown tests:

Compressor discharge total pressure pulldown

Rotor inlet temperature pulldown

HP turbine blade temperature pulldown

FORM 4936 (REV. 11-71)

The purpose of these tests is to exercise limiters at less than limiting values. All other control logic shall operate normally except for the pulled down limit selected.

It shall be possible to exercise the geometry and the fuel valves by operator command. This mode shall be interlocked such that it can be entered only from a 0 speed condition and the fuel "on" discrete will never be commanded during the test. In this test the controller will command each actuation loop and the fuel servos over their respective limits. Pass/fail indications shall be provided via the operating equipment.

6.2 Displays

6.2.1 Engine parameters

The program shall display on command on a DDA-provided CRT the following engine parameters in engineering units.

Parameter	Units
HP rotor speed	%
HP rotor corrected speed	%
Inlet pressure	psia
Compressor discharge total pressure	psia
Compressor discharge static pressure	psia
Compressor discharge Mach number	dimensionless
HP turbine discharge pressure	psia
Engine inlet temperature	°R
HP turbine exit temperature	°R
Turbine blade metal temperature	°R

6.2.2 Controller outputs

The program shall display on command on a DDA provided CRT the following controller outputs in engineering units.

DISTRIBUTION

FORM 4936 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison, Division of General Motors Corporation, Indianapolis, Indiana 46206	EDO NO. REF	PAGE 7 OF PAGES	REPORT NO. AM.1200-001 A
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

Output	Units
Primary fuel command	PPH
Secondary fuel command	PPH
Fuel shutoff	On/Off
HP compressor surge avoidance	inches
HP compressor flow	dimensionless
HP turbine area	dimensionless
Primary nozzle	sq. inches

6.2.3 Failure displays

All self test failures and engine limit exceedances will be displayed via the operating equipment. The presence of a CRT display may be assumed.

7.0 Calibration

Provisions shall be made to calibrate controller inputs and outputs. It shall be possible to adjust gain and offset. These provisions can be effected through hardware, i.e. screwdriver adjustment, or software.

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8.0 Software Test Requirements

8.1 Test plan

A software test plan shall be prepared and submitted to DDA 30 days prior to the planned start of the test. Tests to be included in this plan are explained in later sections.

8.2 Steady state tests

The program, controller and engine model shall be operated at steady state points over the operating range. Control inputs and outputs shall be monitored and recorded.

8.3 Transient tests

The program, controller and engine model shall be operated transiently over the operating range. Transients shall include step functions, ramps and sinusoidal perturbations. The disturbance and controller inputs and outputs shall be permanently recorded on a device of sufficient bandwidth.

FORM 4936 (REV. 11-71)

TECHNICAL DATA REPORT

Detroit Diesel Allison Division of General Motors Corporation Indianapolis, Indiana 46206	EDO NO. REF	PAGE 8 OF PAGES	REPORT NO. AM.1200-001 A
TITLE		PREPARED	DATE
		CHECKED	
		APPROVED	

8.4 Operational test

The operation of each pulldown test shall be verified.

8.5 Induced failures

Each condition that causes an exit to the failure routine shall be simulated. The system's response shall be recorded.

9.0 Documentation Requirements

This section describes the requirements for the software documentation.

9.1 Program description

This is a narrative description of the program's operation. It explains input processing, output calculation and all software self tests.

9.2 Flow charts

All portions of the program shall be flow charted. Annotation shall be sufficient to correlate the listing and the flow chart so that efficient troubleshooting is possible.

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9.3 Listing

An assembly language listing shall be provided. It should contain a list of memory locations, their contents - number and instruction or constant in engineering units. Annotation shall be sufficient to trace the program flow and correlate with the flow charts.

9.4 Parameters

A list of input and output parameters; their I/O channel numbers and their scaling shall be provided.

9.5 Programming Manual

A Bendix 920 programming manual shall be provided. Operation of instructions shall be described. I/O - CPU operation shall be described.

9.6 Mnemonic Glossary

A glossary of all mnemonics used in the software documentation shall be provided.

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